PLANETARY AERONOMY

V: VACUUM ULTRAVIOLET LIGHT SOURCES

by J. A. R. Samson

CONTRACTOR REPORT CR-17

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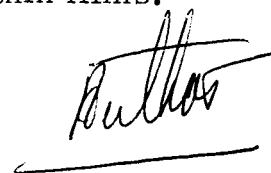
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By J. A. R. Samson
Geophysics Corporation of America
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ABSTRACT

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A study is made of photoelectric detectors, since they pro-
vide a high degree of accuracy in the measurement of absorption
cross sections. The intensity of radiation is often the important
factor in photoionization measurements. The degree of intense-
ness of the radiation, for this study, can be defined as "strong"
if after dispersion by a grating spectrograph the radiant flux
exceeds 10^8 photons/sec at the exit slit. It appears that several
light sources exist which produce useful continua from 3500 A to
600 A of sufficient intensity to measure (employing photoelectric
detection techniques) (a) absorption cross sections of gases and
crystals, and (b) reflectance and transmittance of thin films.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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I. INTRODUCTION

For high resolution spectroscopy it is essential to use a light source which produces a continuous spectrum in the wavelength region of interest. Unfortunately, in the region below 2000 A there are few light sources which produce an intense continuum. Although this is unimportant when photographic techniques are used as detectors, it is very important when photoelectric devices are used. In this discussion we are interested in photoelectric detectors since they provide a higher degree of accuracy in the measurement of absorption cross sections. Further, the intensity of radiation is often the important factor in photoionization measurements.

The degree of intenseness of the radiation, for this discussion, can be defined as "strong" if after dispersion by a grating spectrograph the radiant flux exceeds 10^8 photons/sec at the exit slit. This figure is chosen since, for photoionization measurements below 1000 A, where no window materials transmit, the gases under investigation must be at rather low pressures to maintain the necessary high vacuum in the monochromator and at best about 10 percent of the incident photons are absorbed. Even if a photoionization yield of 100 percent is assumed then even the "strong" radiation of 10^8 photons/sec produces an electric current of only 1.6×10^{-12} amps. A further condition imposed on the intensity of a continuum light source is that the 10^8 photons/sec be

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produced by a dispersing instrument providing a wavelength resolution of one Angstrom or better. This resolution is chosen since line spectra exist with a separation between lines of one to two Angstroms. The many-lined hydrogen spectrum between 900 to 1675 A is an example.

We have discussed the need for light sources which emit a strong continuum in the vacuum ultraviolet region of the spectrum. However, much valuable work can be achieved with a line spectrum especially at the important solar emission lines; viz., the 1215.7 H I, 584 He I and the 304 He II lines. A line spectrum is often more intense than a continuum; and further, it is not always necessary to have a high resolution spectrometer to produce highly monochromatic lines since the separation of the lines may be one or two Angstroms. For instance, a glow discharge in helium produces the intense 584 A line of He I quite isolated from any neighboring lines. Therefore, a resolution of several Angstroms can still produce pure 584 A radiation. It is also easier to assess the amount of scattered light present in a line spectrum than in a continuous spectrum and therefore easier to make corrections for it.

Due to the great variety of experiments in vacuum ultraviolet radiation physics, no single light source would satisfy all experimental requirements nor would it cover the wavelength range of, say, 100 A to 2000 A. In one case a line spectrum may be desired; in another, a microsecond pulse of UV radiation is necessary. However, there are many light source designs which produce similar spectra--some more intense

than others, some with a somewhat different spectral distribution. For instance, the commonly used hydrogen line spectrum between 900 A and 1600 A, excited by a D.C. glow discharge with a platinized capillary, tends to enhance the molecular spectrum whereas a high frequency electrodeless discharge in hydrogen concentrates the spectral energy in the 1216 A Lyman-alpha line.[1] A comparison of the spectra produced in hydrogen and the rare gases by various means of excitation--viz., D.C. glow, microwave generator, and the hot filament type--is presented along with a discussion on light sources which produce continua. This report is not intended to cover all types of vacuum ultraviolet light sources An obvious omission is the Vodar sliding spark source[2] and his newly-discovered continuum.[3] Rather, the intent was to study the production of vacuum ultraviolet radiation by a variety of methods and compare the relative intensity of the radiation on the same spectrometer with a standard slit width and grating. The spectrometer used was a McPherson No. 235 ½ M Seya Monochromator with a 1200 L/mm grating blazed for normal incidence at 1500 A. At the Seya angle of incidence, 35°, this represents a blaze at about 1300 A. The entrance and exit slits were 50 microns wide with the exit slit 6 mm high. A resolution of two Angstroms was realized under the above conditions.

II. CONTINUUM LIGHT SOURCES

A. HYDROGEN CONTINUUM

The hydrogen continuum is best produced in a D.C. glow discharge tube preferably with a platinized capillary to enhance the recombination of atomic hydrogen. A hydrogen pressure of ½ mm Hg is normal to produce a relatively strong continua. As the pressure decreases, the intensity of the molecular radiation decreases whereas the intensities of the atomic lines increase. Details of the D.C. glow discharge tube are given in a later section.

Figure 1 shows the hydrogen continuum from 1675 A to 2300 A obtained from a D.C. glow discharge operated with a current of 300 mA at 200 watts. Superimposed on the continuum are the second order lines of the intense line spectrum above 1050 A. A lithium fluoride window was used in order to remove second order lines due to radiation of shorter wavelength than 1050 A, the transmission limit of lithium fluoride. Thus, a smooth continuum is produced from 1675 A to 2100 A. To extend the usefulness of the continuum to longer wavelengths, quartz or sapphire windows should be used since their transmission limits are 1800 A and 1400 A, respectively. The dashed line in Figure 1 represents the continuum in the absence of the second order lines. Below 2000 A the peak radiant flux of the continuum is 1.6×10^7 photons/sec. For comparison, the intensity of the Lyman-alpha line, 1215.7 A, and the

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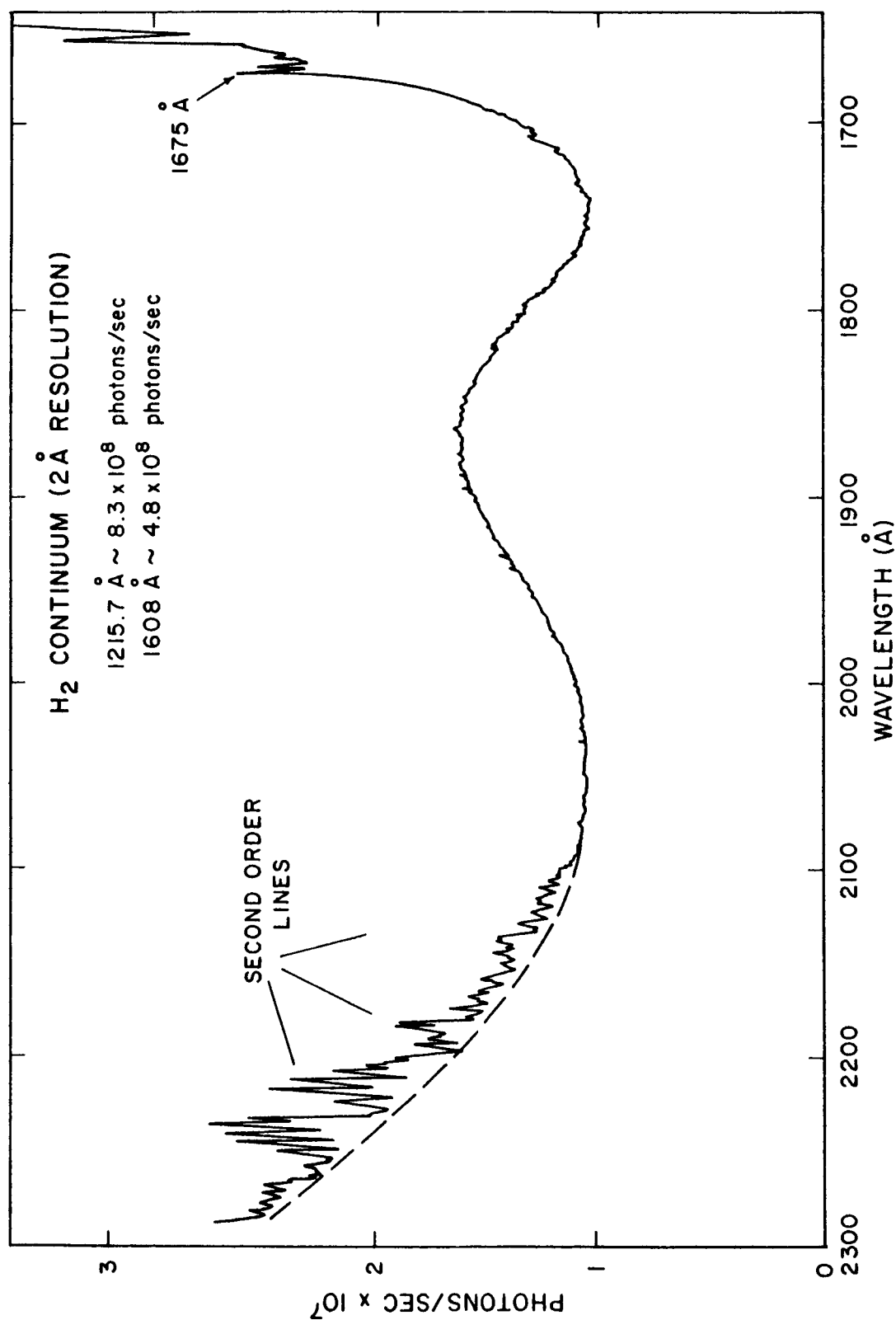
Figure 1. The hydrogen continuum transmitted through a lithium fluoride window. The dashed line indicates the H$_2$ continuum when the second order lines are removed.

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molecular band at 1608 A is given in Figure 1. However, the relative intensities of these lines and the continuum vary with pressure.

B. RARE GAS CONTINUA

Several rare gas continua have been produced by Tanaka et al.[4] covering the range 600 A to 2000 A. No estimates of the absolute intensities are available, however, since the method of detection was by photographic techniques.

Recently, Huffman et al.[5,6] at the Air Force Cambridge Research Laboratories successfully produced a relatively strong continuum using a condensed repetitive spark in purified helium. To obtain this continuum, the helium pressure was rather high (around 50 mm Hg); thus, differential pumping was required to maintain a high vacuum in the main body of the spectrograph. In addition to the normally observed Hopfield continuum,[7] between 600 and 1000 A, they observed another helium continuum between 1050 and 4000 A which they report has a peak intensity eighty times more intense than the peak in the Hopfield continuum.[8]

Absolute intensity measurements of the Hopfield continuum were made as follows: A photomultiplier coated with sodium salicylate was used to record the continuum along with the 1216 A impurity line; then, by extrapolating the constant quantum yield of sodium salicylate[9] below 900 A, the intensity of the continuum was determine relative to the 1216 A line. A nitric oxide ion chamber was then used to determine the absolute intensity of the 1216 A line from the known photoionization yield of nitri:

oxide.[10] The peak flux of the continuum was found to be approximately 3×10^7 photons/sec when used with a 2 M normal incidence spectrograph, 600 lines/mm grating, and 0.1 mm entrance and exit slits. This provided a wavelength resolution of 0.5 Å. Figure 2--kindly supplied by Dr. Huffman--shows the Hopfield continuum with the Ne I and hydrogen series impurity lines.[11]

Other examples of rare gas (xenon, krypton, and argon) continua[12] are shown in Figure 3 which is reproduced from the Jarrell-Ash catalog. In the present investigation, the absolute flux produced by the Jarrell-Ash xenon lamp was measured under the standard conditions described in the Introduction and found to be 1.5×10^7 photons/sec at the peak of the continuum around 1670 A.

    C. LYMAN CONTINUUM

The conventional source of continua below 1000 A is the Lyman flash tube.[13] This is essentially an impulsive discharge from a capacitor through a narrow bore capillary, with an external gap in series to give a high breakdown voltage. As the power is increased, the continuum extends to shorter wavelengths. Photographically, it has been observed down to about 200 A. This type of flash tube has many drawbacks; for instance, the erosion of the capillary is so rapid that it is difficult to obtain reproducible intensities from flash to flash. Further, the eroded material can damage the grating of the spectrograph. Garton[14] has overcome these difficulties to a certain extent by using

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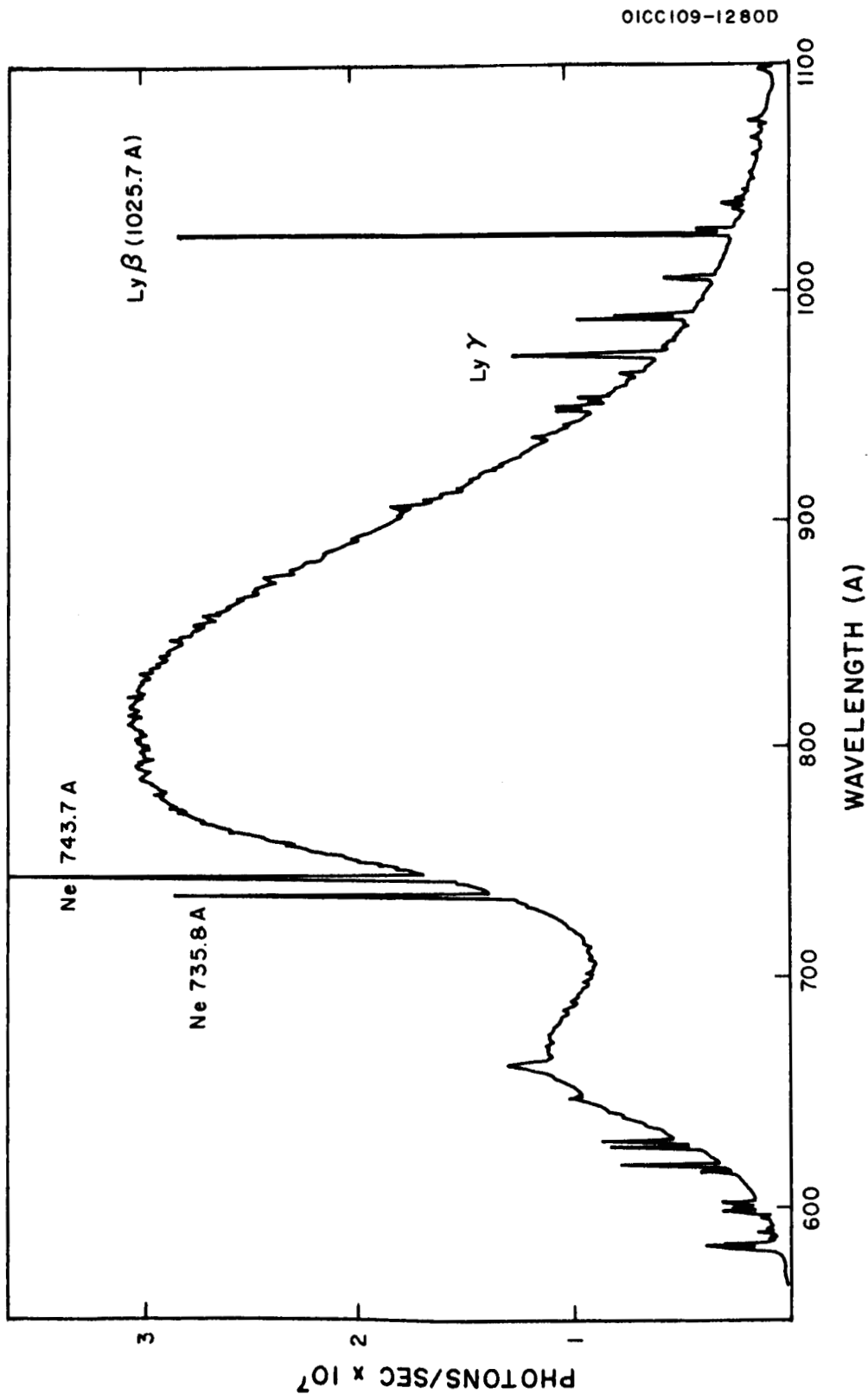
Figure 2. Hopfield continuum between 600 and 1000 A. Impurity lines of atomic hydrogen and neon are present in the helium discharge.

XENON

1M Vac. Scan. Spectrometer
Slit 15μ
Scan 50 A°/min
Air Pressure > 1mm
Path 5 mm
Source Xe

WAVELENGTH A°
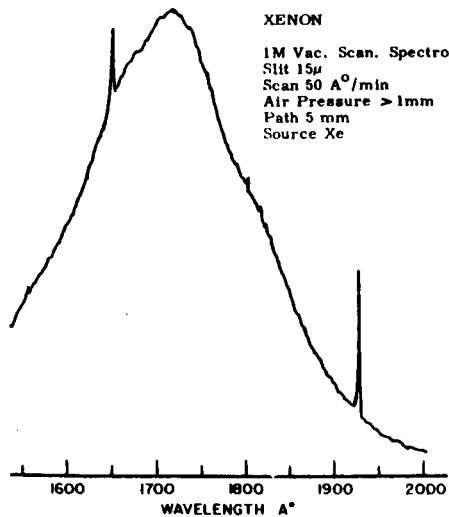
USEFUL RANGE 1600 - 1950 A
WITH LITTLE LINE EMISSION
Catalog No. 45-503

KRYPTON

0.5M Seya-Namioka Vac.
Monochromator
Slit at 30μ
Scan 25 A°/min
Air
Pressure > 1mm
Path 5 mm
Source Kr

WAVELENGTH A°
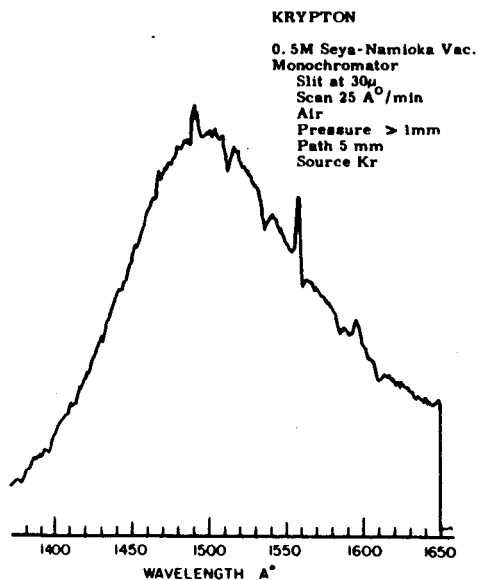
USEFUL RANGE 1300 - 1650 A
WITH LITTLE LINE EMISSION
Catalog No. 45-502

ARGON

0.5M Seya-Namioka Vac.
Monochromator
Slit at 50μ
Scan 100 A°/min
Source Ar
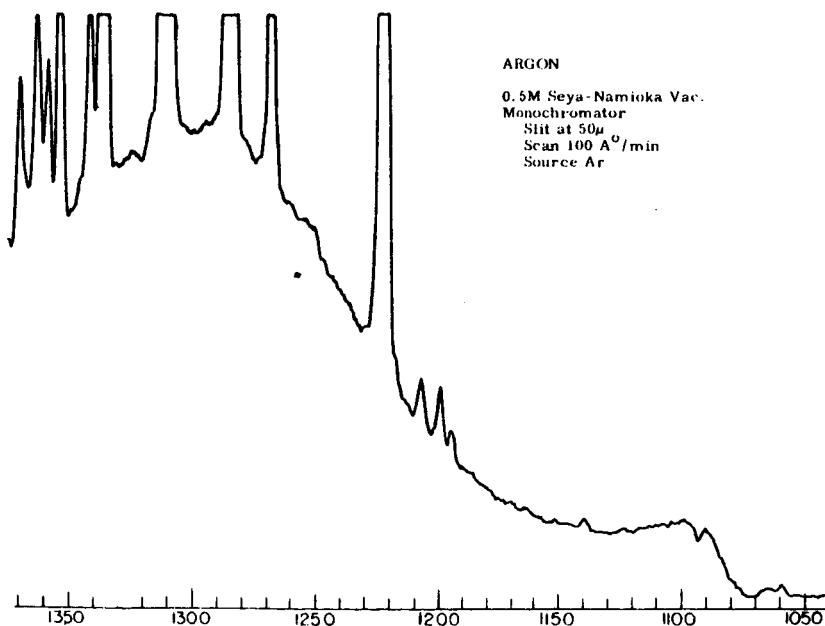
USEFUL RANGE 1090 - 1300 A
RATHER SEVERE LINE EMISSION
BUT STILL USEFUL
Catalog No. 45-501

Figure 3. Rare gas continua produced by xenon, krypton, and argon at
approximately 150 mm Hg pressure in LiF sealed lamps. The
absolute flux at the peak of the xenon continuum is about
1.5×10^7 photons/sec.

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a wider bore tube (1 cm) but maintaining the necessary high current density to produce a continuous spectrum by using a more efficient design of the flash tube. This is achieved by keeping the inductance in the circuit to a minimum. The flash tube has a coaxial construction and the capacitor is a specially designed low inductance type. Photoelectrically, the continuum is useful from the visible to approximately 1000 A. A comparison of various types of flash tubes is given by Parkinson and Reeves.[15]

The Garton-type flash tube described here removes the problem of rapid wall erosion affecting the light intensity. This is achieved by using a capillary of larger bore than in the usual type of Lyman flash tube. To compensate for the larger bore, a more efficient design of tube is used to maintain the necessary high current density of at least 3×10^4 amps/cm^2 to produce continuum radiation. Figure 4 shows an assembly drawing of the Garton-type flash tube. The construction is coaxial to minimize inductance and since

$$i = \frac{E}{wL} \exp (- \alpha t) \sin wt \qquad (1)$$

for an oscillatory capacitor discharge, then the current, i, increases as the inductance, L, decreases. E is the capacitor voltage, w equals 2π times the ringing frequency (f) of the discharge, while α is a decay constant equal to R/2L. Hence, for small L, the decay of the oscillations is more rapid and essentially more and more of the capacitor energy

Scale = 1"

TRIGGER PIN

PYREX "O" RING JOINT

TEFLON INSULATOR

PLEXIGLASS WATER JACKET

CERAMIC CAPILLARY

O-RING

HOUSING TUBE

WATER IN

NYLON SCREWS

GAS IN →

PYREX TUBE

RING PLATE

PARALLEL PLATE TRANSMISSION LINE
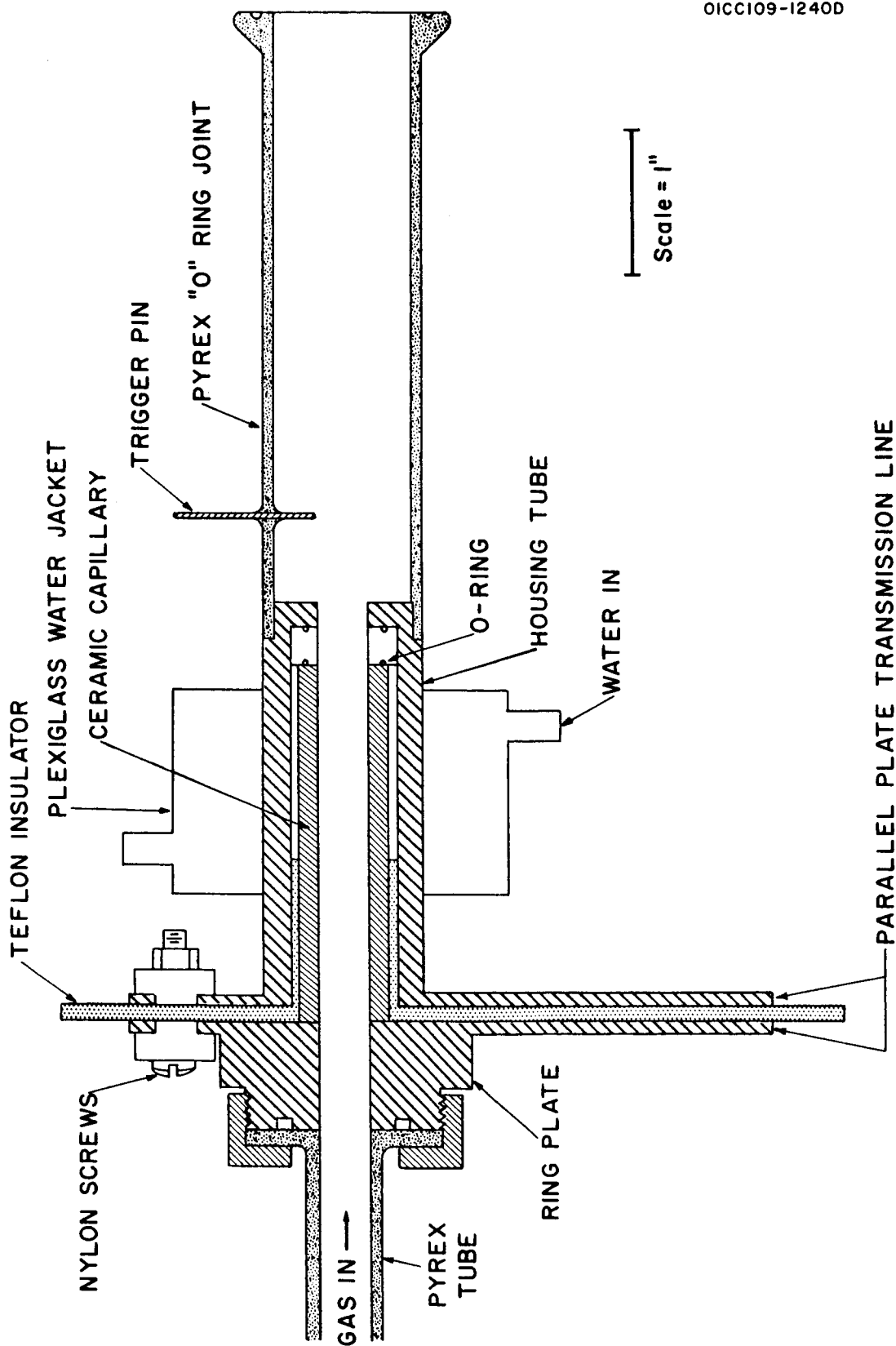
Figure 4. Garton-type flash tube.

goes into the first few cycles of the discharge. The electrodes form a parallel plate low inductance transmission line.

The housing tube is the ground electrode while the ring plate is connected to a positive voltage. The pressure inside the capillary is maintained at approximately 50 microns which is sufficiently low that no spontaneous discharge takes place. The trigger electrode is then used to initiate the discharge. Helium gas was used as it is the most transparent in the vacuum UV region. The continuum is, however, produced regardless of the gas used and the line spectrum is due to impurities present in the tube; viz., O_2 and C. The discharge takes place through the 9 mm bore 6.5 cm long ceramic capillary which is sealed vacuum tight to the electrodes by O-rings. The O-rings limit the temperature of the flash tube which has to be water-cooled if operated as frequently as 1 pps. Ceramic-to-metal seals would be an obvious improvement although more inconvenient to renew. A breakdown of the major components of the flash tube is shown in Figure 5. The Pyrex tube has now been replaced by a No. 20 Pyrex O-ring joint. Figure 6 shows an assembled flash tube complete with Plexiglass water jacket, while Figure 7 illustrates how the flash tube is connected to the low inductance capacitor via a parallel plate transmission line.

The flash tube can be automatically or manually fired. In Figure 8, a circuit diagram is given illustrating the trigger circuit and how it is connected to the flash tube capacitor circuit. Basically, the principle of operation is as follows. As the flash tube capacitor

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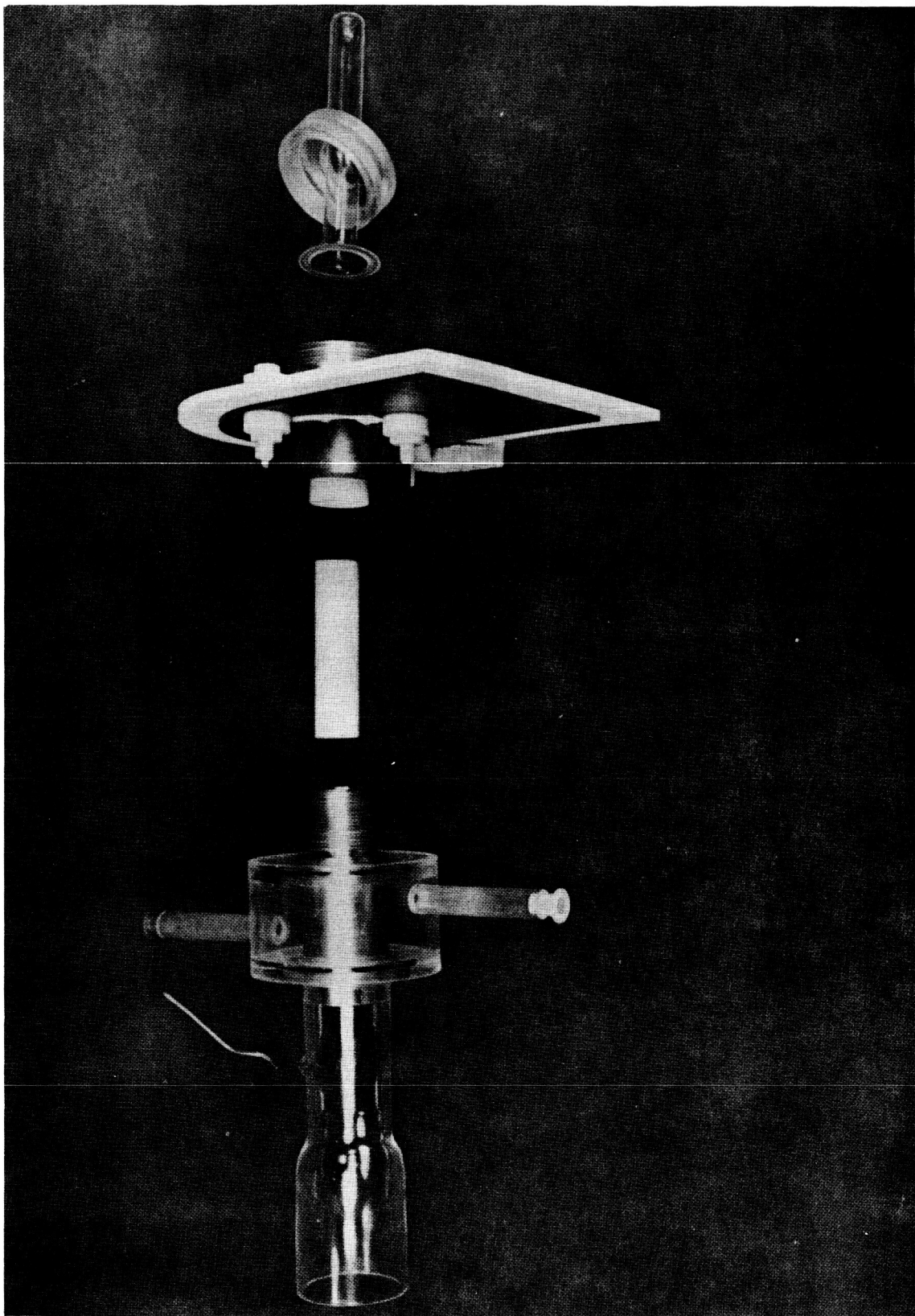
Figure 5. Breakdown of major components of flash tube.
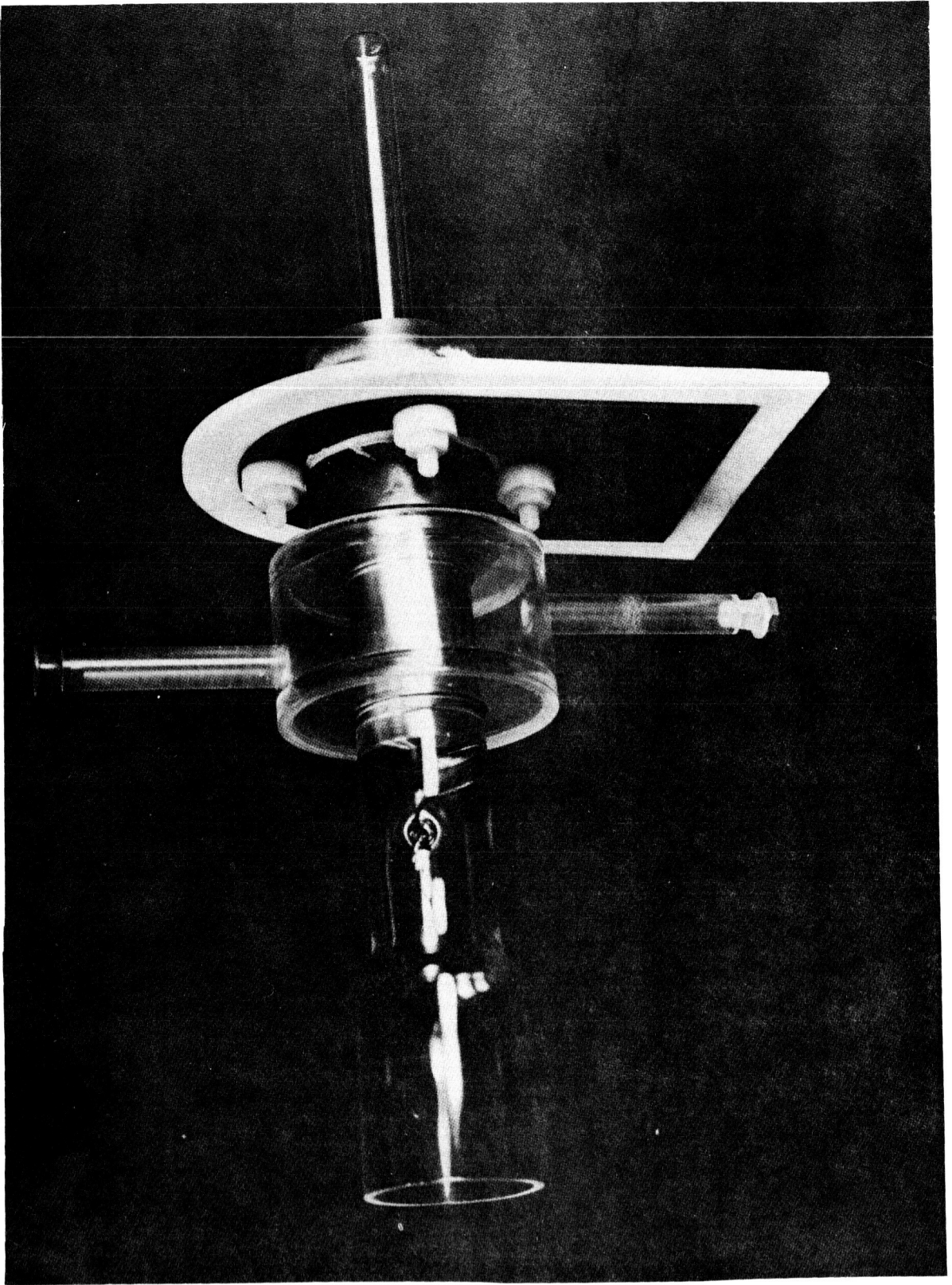
Figure 6. Assembled view of flash tube.

14
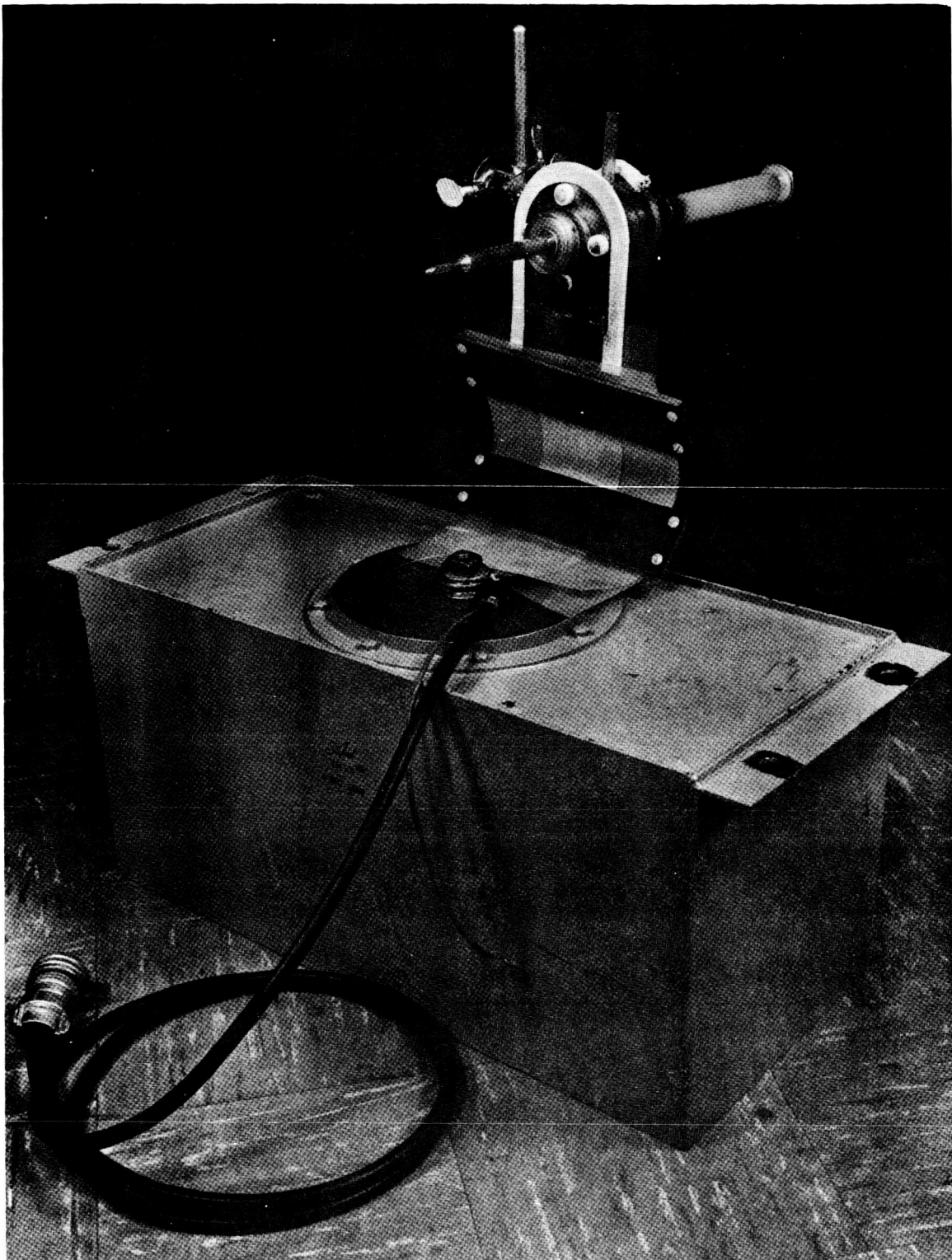
Figure 7. Flash tube and storage capacitor showing the
low inductance transmission line.

FLASH TUBE TRIGGER CIRCUIT

Figure 8. Trigger circuit utilized for the Garton-type far UV light source.

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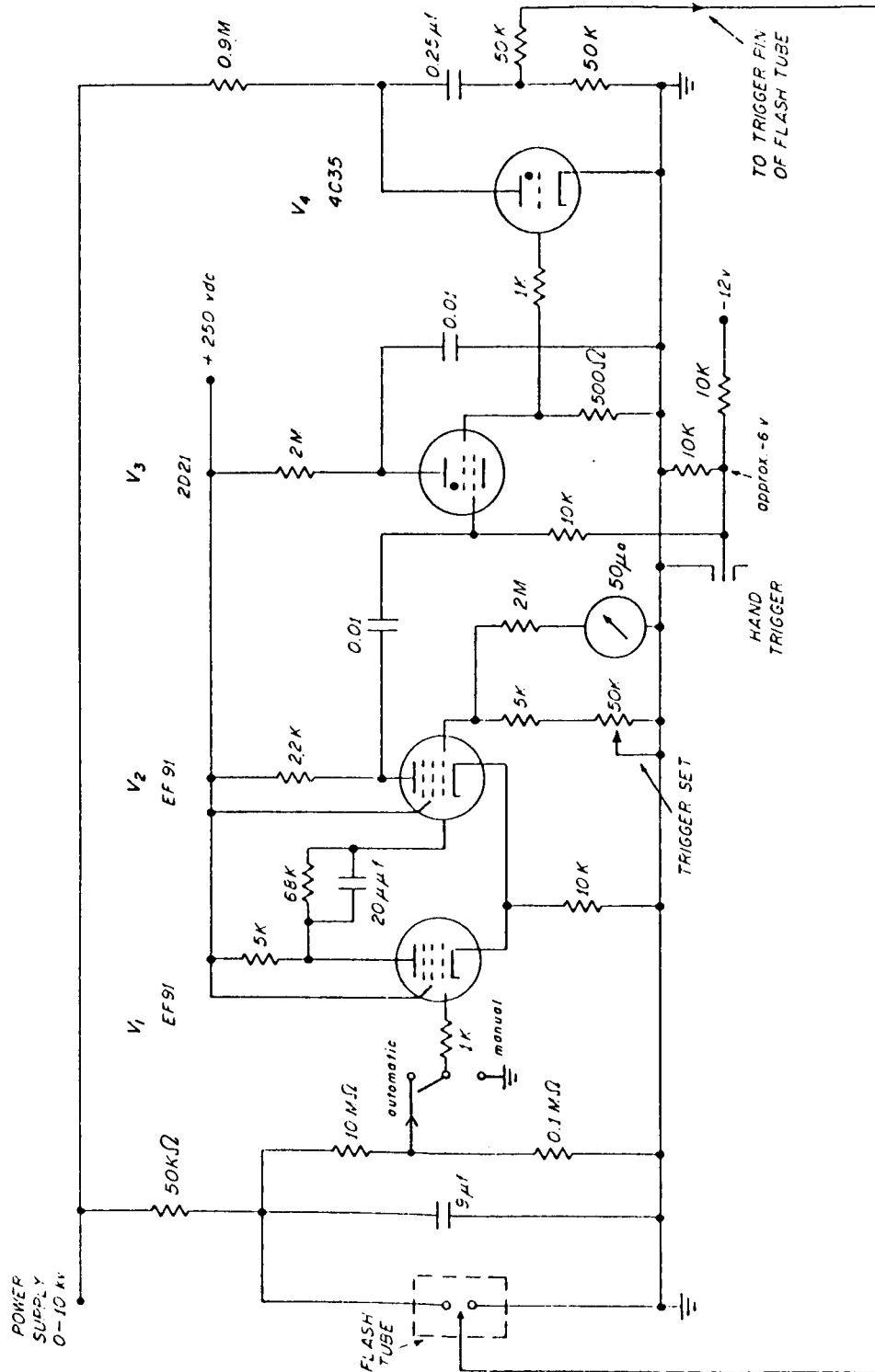
(9μ f) charges, the voltage across the 0.1 M Ω of the capacitor voltage divider reaches a sufficiently positive potential to start V_1 into its conducting phase. The plate current of this tube increases, thereby reducing the positive grid bias of V_2 until it is insufficient to maintain conduction in V_2. At this point, a positive pulse is transmitted to the grid of the 2D21 thyratron tube which ignites and triggers the hydrogen thyratron tube 4C35. With the firing of the 4C35 tube, the trigger capacitor (0.25μ f) discharges rapidly through it; and the pulse developed across the 50 K resistor is applied to the trigger pin, thereby firing the flash tube. The flash tube is maintained at a sufficiently low pressure (approximately 50 μ) to stand off the high voltage and requires the triggered pulse to fire the tube.

A hand trigger is inserted when only individual flashes are required; e.g., in spectrographic work.

The variable resistor marked "trigger set" adjusts the positive grid bias of V_2, and thus the point on the RC charging curve at which the flash tube capacitor will discharge through the flash tube.

A typical spectrum obtained with the flash tube is shown in Figure 9 for one, two, and four discharges, each discharge lasting about a microsecond. The spectrum was obtained on a 2 M vacuum spectrograph (McPherson No. 240) with a 600 L/mm grating blazed for 1500 A. The entrance slit was 100 μ wide. The 9 μ f capacitor was charged to 8 kv.

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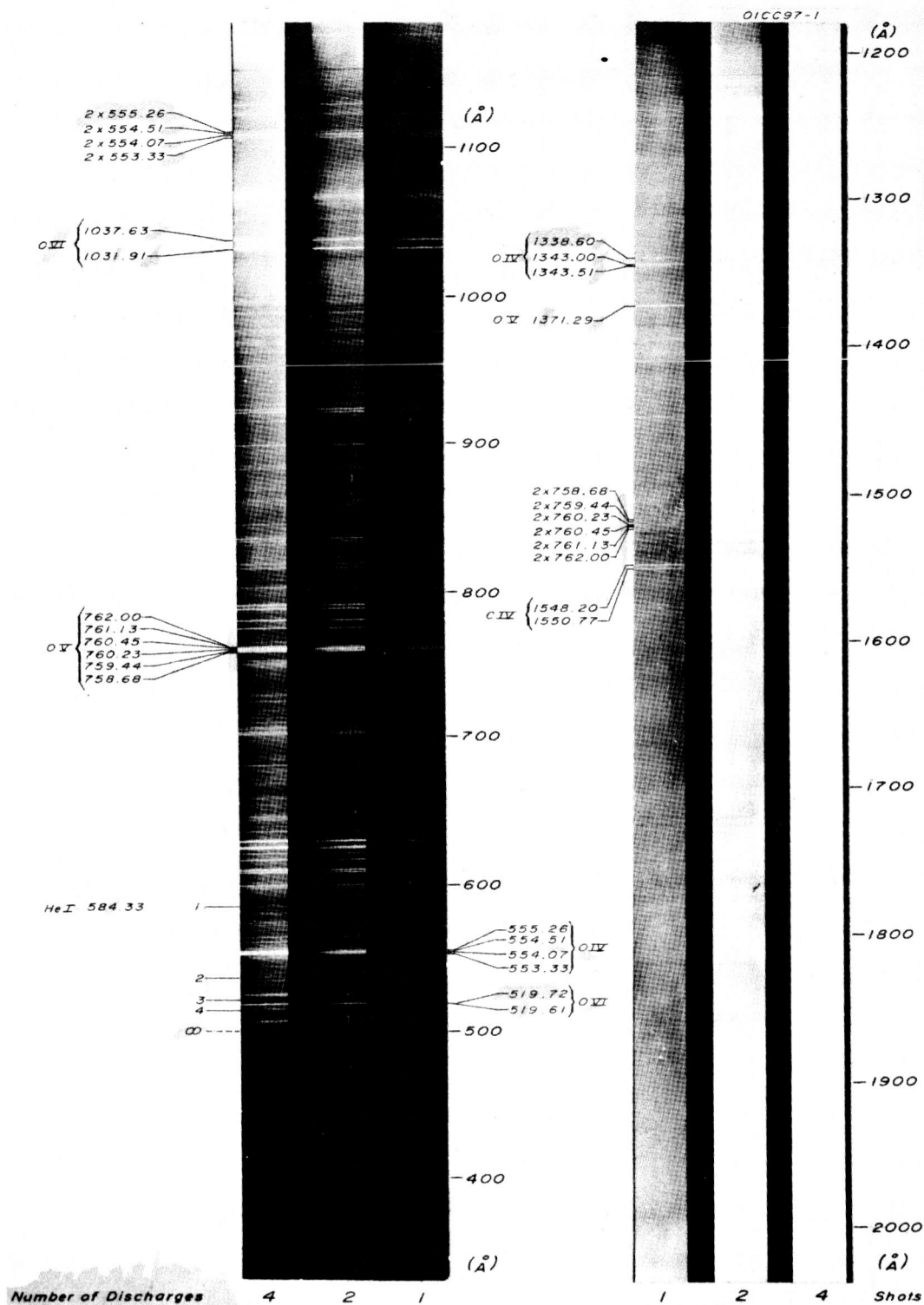
Figure 9. Flash tube spectrum of helium between 500 and 2000 A. Exposures for one, two, and four discharges are shown. The line spectrum is due to impurities; namely, oxygen.

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A usable continuum extends from the visible to below 1200 A even for a single discharge. Below 1200 A the continuum is superimposed with an intense line spectrum. However, the continuum is observed to go down to about 500 A, at which point the absorption of the He ionization continuum starts and the grating efficiency for normal incidence is close to zero. In the original negative, with four discharges, lines are observed down to 300 A. It is interesting to note that there is sufficient neutral helium in the Pyrex tube of the flash tube to produce a Rydberg series in absorption of the 584.3 He I series illustrating the usefulness of the continuum for absorption studies even in this short wavelength region. The presence of such highly ionized species as O V and O VI demonstrates the high temperatures achieved in the flash tube.

In Figure 10, oscilloscope traces of the discharge current and light intensity (555 A) as a function of time are shown. The sweep time is 2 μ sec/large division. From the light output oscillogram, it can be seen that 70 percent of the light intensity takes place within 2 μ sec.

To measure the peak current during the discharge, the following procedure is followed. From the ring frequency of the current oscillogram, the logarithmic decrement can be found; viz.,

$$\ln \text{ dec } = \ln (i_1/i_2) \tag{2}$$

where i_1 and i_2 are the peak values of the first and second half cycles of the current oscillations.
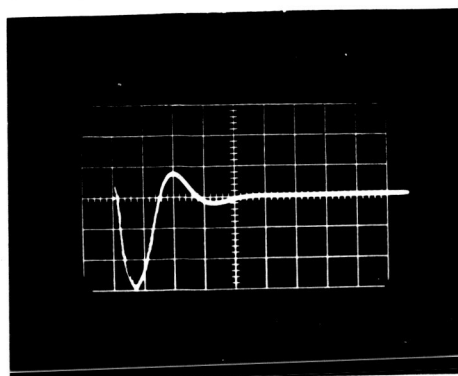
DISCHARGE CURRENT
VS.
TIME

(2 μ sec/major division)
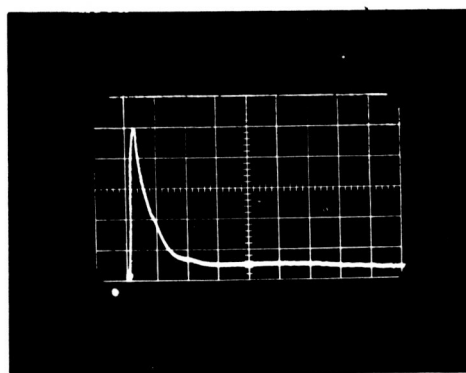
LIGHT OUTPUT (555 A)
VS.
TIME

(2 μ sec/major division

Figure 10.   Oscillograms of the current an
             light output of the flash tube

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From Eq. (1).

$$\ln (i_1/i_2) = \frac{\alpha}{2f} \qquad\qquad (3)$$

The ring frequency, f, is found to be 190 kc; hence, α is found. The time for the current to reach a maximum can be measured from the oscillo-gram; thus, all the unknowns in Equation (1) are determined and i_{max} is found to be

$$i_{max} = 57 \text{ kamps}$$

This gives a current density of approximately 90 kamps and a total inductance for the circuit of about 66 m μ h.

The flash tube appears to be an excellent source of continuum radiation from the visible down to approximately 1000 A. The short duration of the light pulse and the ability to trigger the discharge at any precisely required time makes this type of light source particularly suitable for absorption studies in such transient phenomena as found in shock tube research and possibly in measuring reaction rates greater than 1 μ sec.

III. LINE EMISSION LIGHT SOURCES

A. D.C. COLD CATHODE DISCHARGE

In a cold cathode gas discharge, several hundred volts must be applied to the electrodes; then when a free electron exists in the tube, it will be accelerated until it accumulates sufficient energy to cause ionization in the gas. This process multiplies and a Townsend avalanche is formed. In order for the discharge to be self-sustaining, the positive ions must receive enough energy to produce secondary electrons when they impinge on the cathode. Thus, in the glow discharge region, much higher voltages are required to sustain a discharge than in the arc region where the electrons are produced by temperature emission from a hot cathode--the cathode being heated either by ion bombardment or by an electric current as in a hot filament.

A common design for a cold cathode discharge tube is to use a water-cooled quartz or Pyrex capillary sealed into a hollow cathode and anode by O-rings. However, the cold cathode discharge tube described here was based on a design by W. Hunter[16] of the Naval Research Laboratories. It differs from the more conventional type in that it uses a water-cooled cathode and allows the quartz capillary to run hot rather than cooling the capillary with a water jacket. The main advantage of this feature is that there is no danger of water entering the vacuum system should the capillary break.

Figure 11 shows a breakdown of the discharge tube. Basically, the light source consists of a 4" quartz disc with a quartz capillary (4 mm bore) sealed into the disc through its center and normal to its surface. The quartz disc is ground flat to seat the O-rings on the cathode and the anode, and acts as an insulator as well as a vacuum seal. The cathode--the left-hand cylinder in Figure 11--is constructed of two concentric cylinders sealed to allow water to flow between them. A hollow aluminum cylinder is seen protruding from the cathode and actually acts as the cathode electrode, allowing easy replacement if necessary. The aluminum insert has a few very fine holes to allow the discharge gas to leak into the discharge region. The anode--extreme right--is hollow and flanged to mate the spectrograph. A small window is inserted for visual observation. A Plexiglass flange is used to clamp the components together and is grooved to locate the quartz disc such that the capillary lies on the axis of the spectrograph. Figure 12 illustrates the complete discharge lamp.

The lamp has been in continuous use for many months with no maintenance required and has proved to be very rugged. When operated in the glow-discharge region for hydrogen--between 200 and 300 mA at 700 V for this particular lamp--the light intensity is very stable, using only a voltage-regulated power supply. However, above 300 mA, the discharge enters the arc-discharge stage where the voltage across the lamp decreases as the current increases and the light output shows considerable noise. In this region current stabilization would be desirable since the light output is a function of the discharge current.
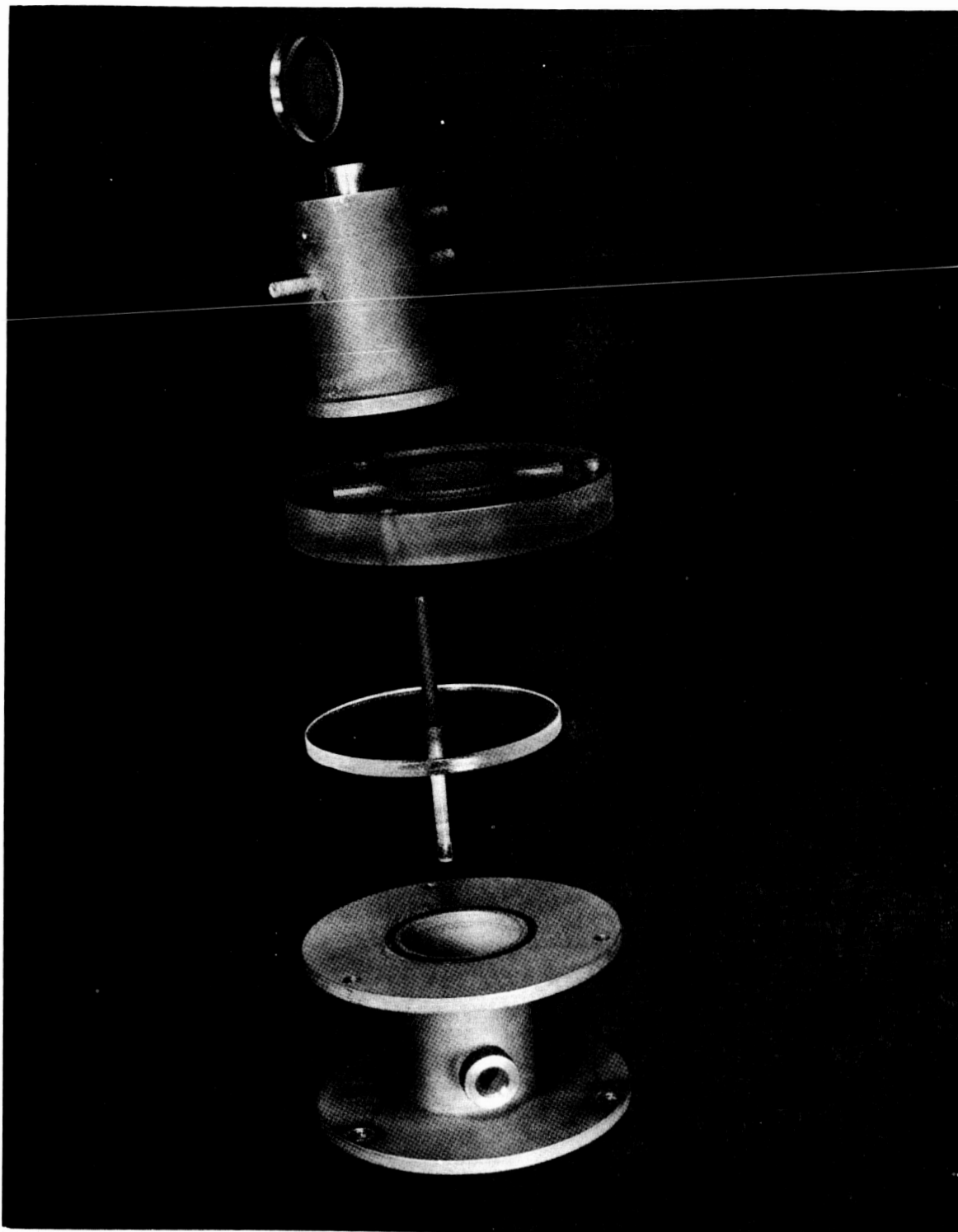
Figure 11.   Breakdown of the major components of the discharge lamp.
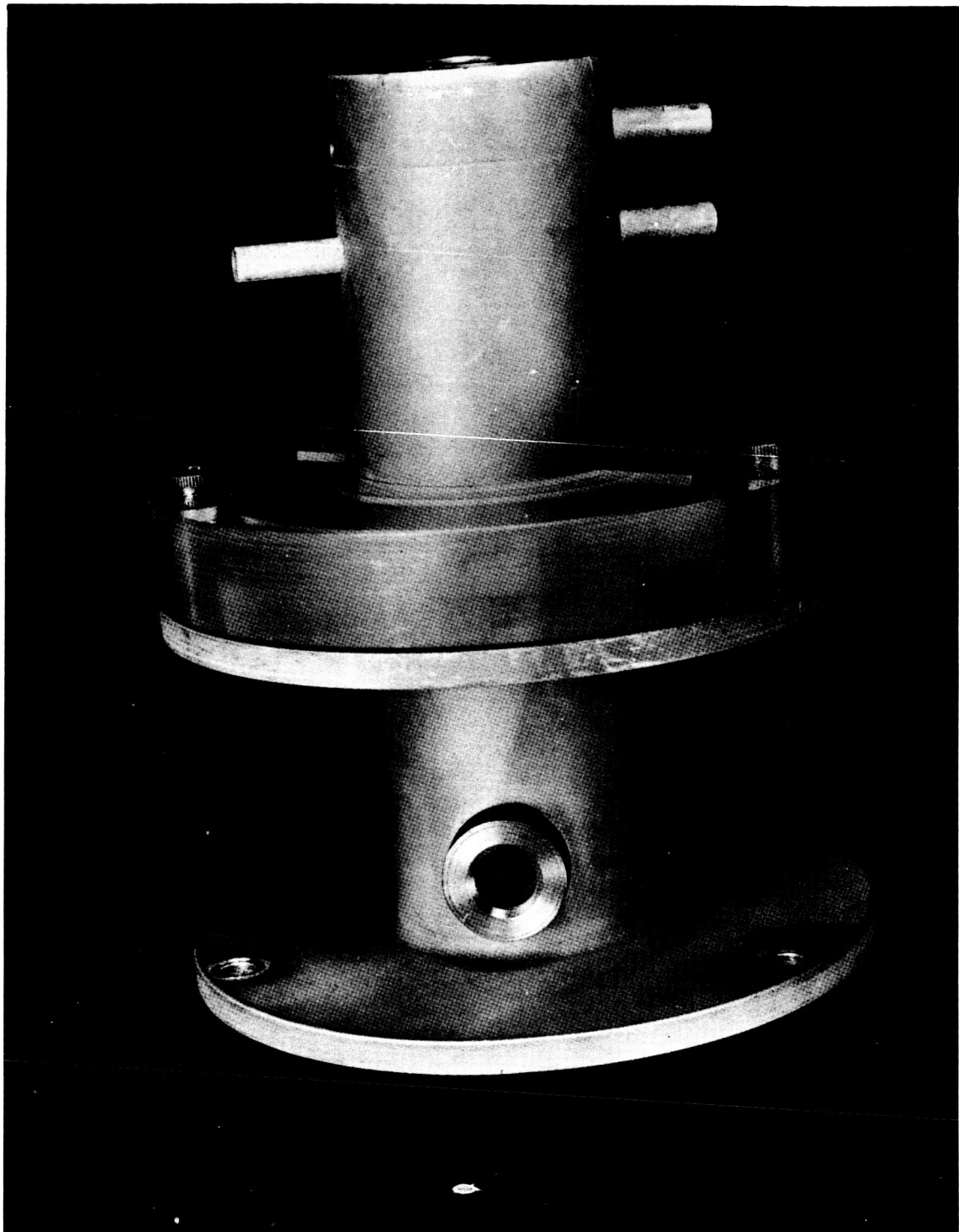
Figure 12.   Complete discharge lamp.

The cold cathode discharge light source is very suitable in exciting molecular lines and the resonance lines of atoms. The molecular lines can be enhanced if the capillary interior is slightly metallized. However, it is not so suitable in producing radiation from the more highly ionized atoms. Since the source of radiation below 1000 A is due mainly to highly ionized atoms, the usefulness of the glow-discharge lamp is mainly above 1000 A, with the exception of the He I 584 A and Ne I 735.8 and 743.7 A resonance lines.

Figure 13 shows a typical hydrogen spectrum recorded by an EMI 9514B photomultiplier sensitized to vacuum UV radiation by coating with sodium salicylate. The spectrum is mainly due to molecular hydrogen; however, the resonance lines, Lyman-α and β, can be seen. The actual spectral energy distribution shown here is, of course, dependent on the individual grating used.[17] The absolute flux at Lyman-α was measured with a nitric oxide ionization chamber and since the quantum yield of sodium salicylate is relatively constant[9] between 1000 and 2000 A, the photomultiplier trace gives the absolute flux of the radiation emanating from the exit slit. The spectral response above 1300 A is well known and is not reproduced here. The spectrum was taken with 50 micron slits on a ½ M Seya Monochromator (McPherson 235). A resolution of about 2 A is realized.

Using exactly the same parameters for the monochromator, the helium glow-discharge spectrum was investigated and compared to the intensity of the hydrogen spectrum. The spectrum is shown in Figure 14
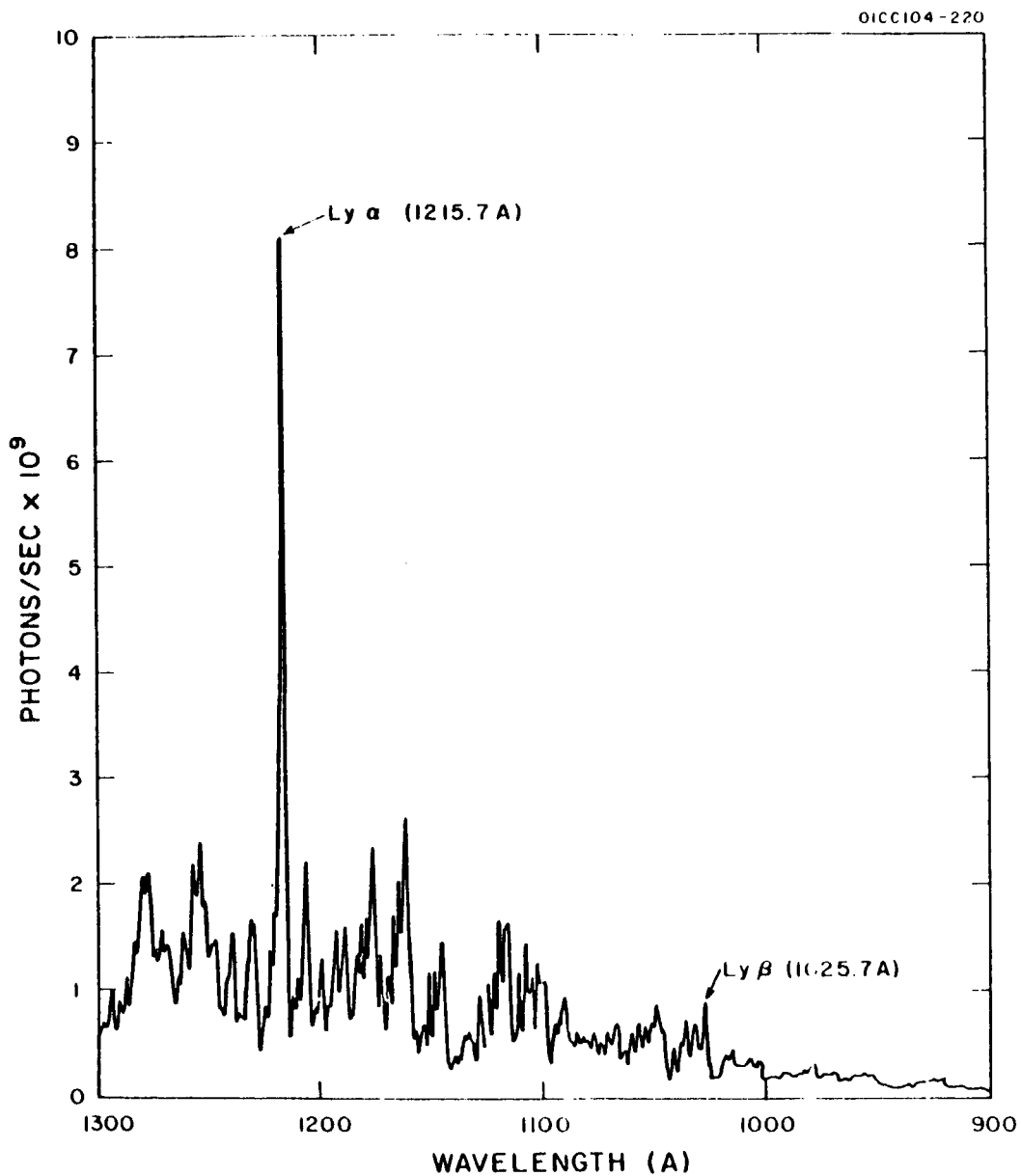
Figure 13. Hydrogen spectrum between 900 and 1300 A. The important solar emission lines of Lyman-α (1215.7 A) and Lyman-β (1025.7 A) are shown.
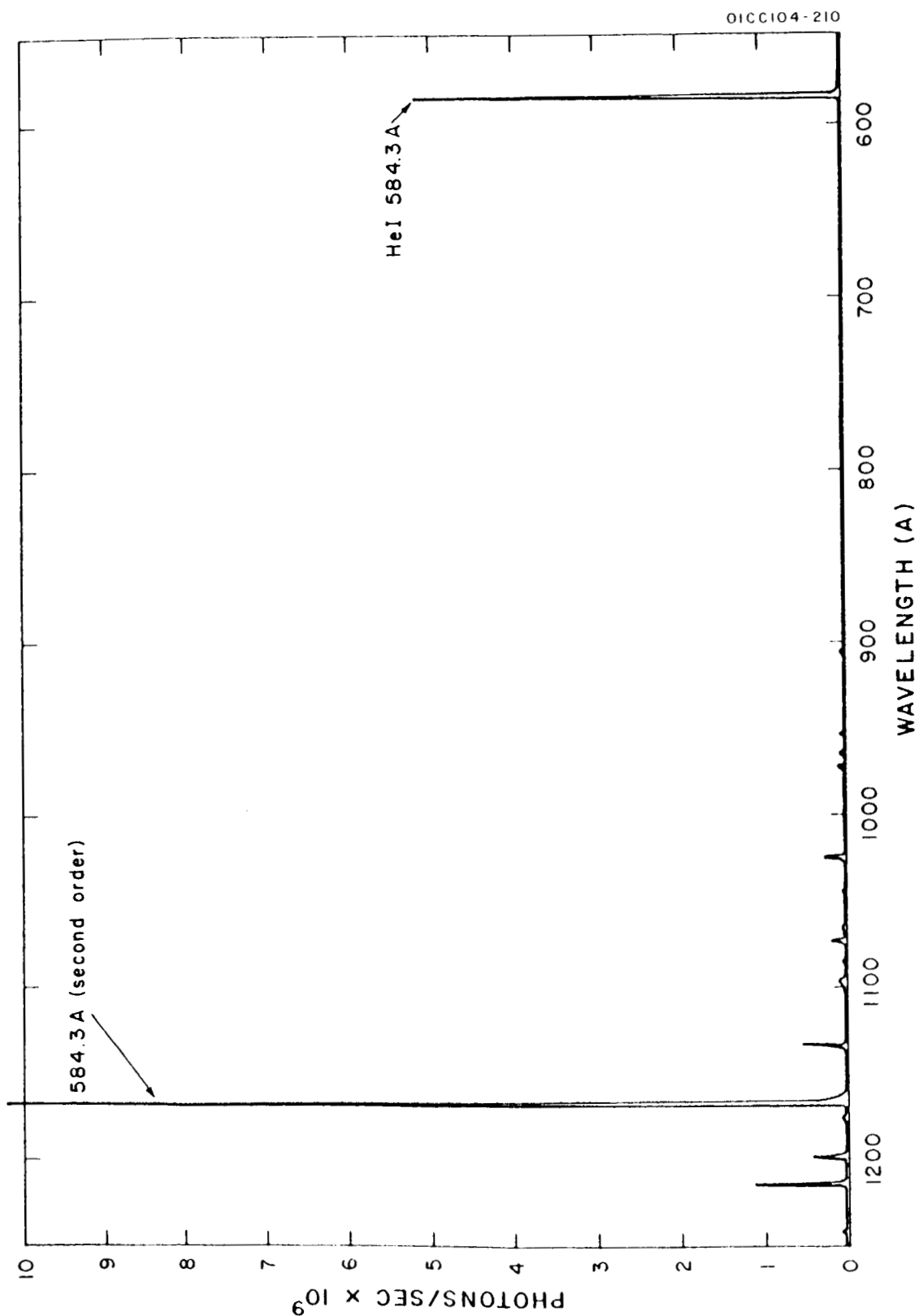
Figure 14. Glow-discharge spectrum in helium between 550 and 1200 A showing both first and second order of He I (584.3 A).

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Its usefulness is in producing the He I resonance line at 584.3 A with considerable intensity. The second order 584 A line is more intense than the first order, indicating that this grating is more efficiently blazed in the region of 1200 A than to shorter wavelengths. The grating was blazed for 1500 A at normal incidence; but for a few weak impurity lines, the helium spectrum below 1300 A is concentrated solely in the 584.3 A line. The absolute photon flux at 584.3 A was obtained by assuming that the quantum yield of sodium salicylate remained constant down to 584 A [9]

An argon spectrum was investigated and found to produce--in addition to the A I resonance lines at 1048 A and 1066 A--many lines of shorter wavelength down to 500 A. In fact the spectrum below 1000 A is very similar to that produced by the Duoplasmatron, shown in Part C of this section. However, the intensities were at least an order of magnitude lower than that produced by the Duoplasmatron. Typical values of the radiant flux are given below for a 270 watt glow discharge in argon operated at 300 mA

Wavelength (A)	Origin	Flux in Photons/Sec
1066	A I	3.60×10^8
1048	A I	6.30
920	A II	0.52
671	A II	0.03
573	A II	0.003

It would appear, therefore, that the glow-discharge lamp is admirably suited to produce the profuse hydrogen line spectrum from 900 to 1675 A, the hydrogen continuum above 1675 A, and atomic resonance lines including the He I resonance line at 584.3 A and the Ne I lines at 735.8 A and 743.7 A. For other line radiation below 1000 A, another type of light source must be used.

B. HOT FILAMENT ARC DISCHARGE

The use of hot filaments to provide the free electrons necessary to sustain a discharge in hydrogen and other gases has been described in the literature.[18,19] The main advantage in using a hot filament to produce an arc discharge appears to be due to the fact that a discharge current of several amperes can be created by low voltages, typically 50 to 100 V. Thus, the need for a high voltage power supply is eliminated. A typical 150 V - 5 A power supply is shown in Part C of this section and could easily be constructed by most laboratories. Should a higher degree of current stabilization be required, an excellent circuit is given by Moak et al.[20] On the other hand, a prime disadvantage is the need to renew the filaments periodically due to a decrease in their electron emission. However, with some experience this does not present a major obstacle.

The one comparison, between the hot filament arc discharge and other types of discharges that has rarely been expressed is that of light intensity in the vacuum ultraviolet region and of the origin of the radiation; viz., molecular, atomic, neutral or ionized atoms. It is the purpose

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of this report to compare the intensity and type of spectrum produced by discharges excited by different methods.

The arc discharge described here is based on the design used by P. Hartman.[19,21] Figure 15 shows the lamp assembly. The filament is a helically coiled nickel ribbon dipped in barium carbonate and activated in a hydrogen atmosphere. A trigger pin is inserted in the quartz discharge tube to strike the arc initially. A Tesla coil is suitable to trigger the discharge. The filament draws approximately 12 A at 4 volts, while the voltage across the discharge is about 90 V when an arc current of 3 A is being passed in hydrogen. Thus, the light source can be operated at 270 watts. The D.C. glow discharge described in Part A was operated at approximately 240 watts.

Although the arc discharge produces a strong hydrogen molecular spectrum, the atomic resonance line is by far the most intense line. Using the standard ½ M Seya monochromator with 50 micron slits, the 1216 A line produced 10^{10} photons/sec. which is at least 50 percent of the total radiation between 1350 A and 1050 A. Further, the higher members of the Lyman series of atomic hydrogen, Beta and Gamma, appeared clearly above the weaker molecular bands.

By using a mixture of hydrogen and helium in the discharge-- approximately 25 percent hydrogen--the radiation becomes nearly monochromatic in the Lyman-alpha line at 1216 A. Actually, the intensity of the atomic lines in the pure hydrogen discharge did not change appreciably
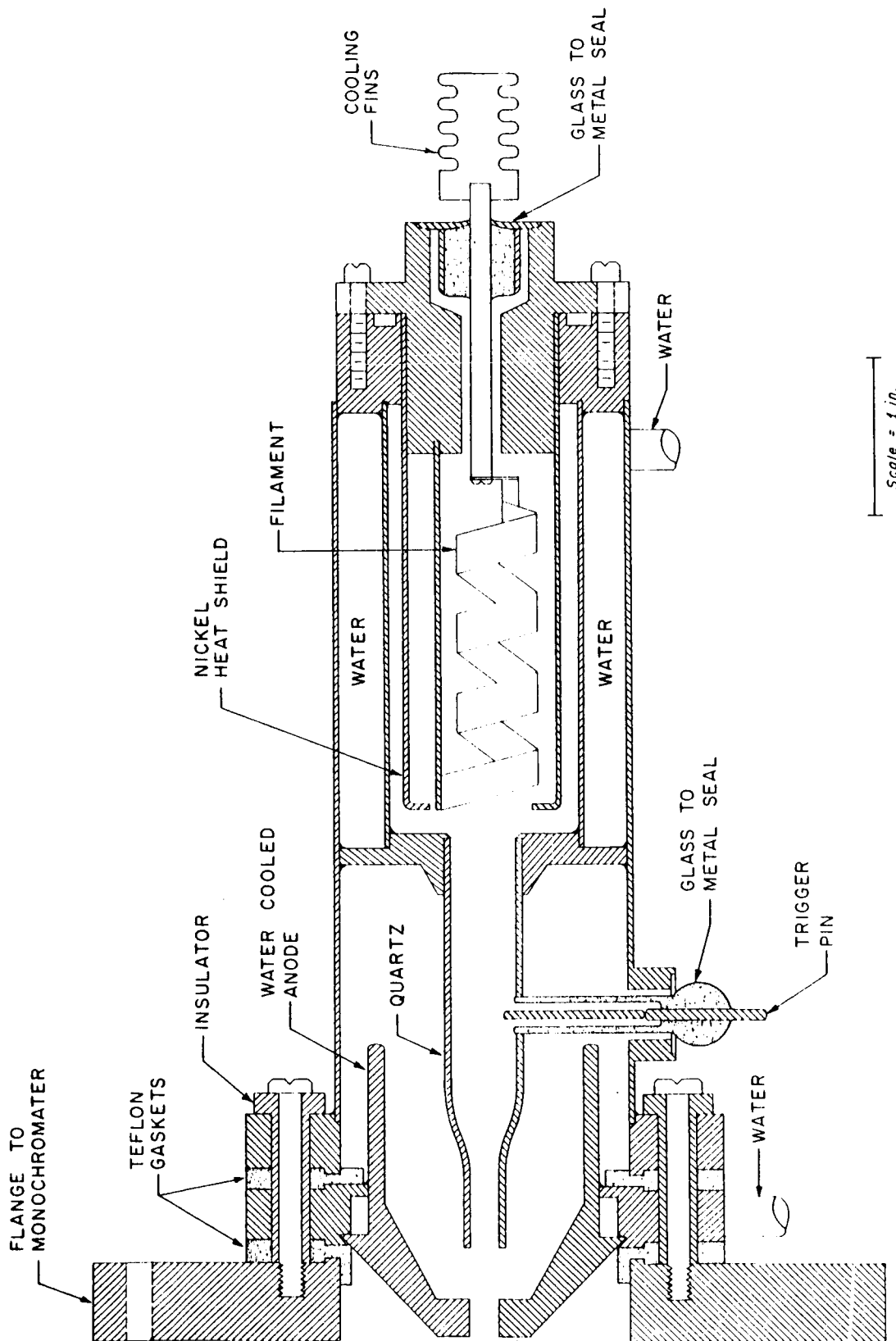
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Figure 15. Hot filament discharge lamp.

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when helium was added; however, the intensities of the molecular lines were greatly reduced. Figure 16 shows the Lyman series of atomic hydrogen when a hydrogen-helium mixture was used in the arc discharge.

When a discharge in argon was studied, the argon resonance line at 1048 A and the 1066.7 A line appeared with good intensity although about an order of magnitude less intense than the hydrogen 1216 A line. The resonance line of ionized argon at 919.8 A also appeared along with many weaker lines to shorter wavelengths. Unfortunately, with argon this particular lamp would not operate properly, but presumably the argon lines appeared down to about 500 A as they do in the glow discharge. If the argon lines are of usable intensity, then this is one of the major advantages of the hot filament arc discharge. Normally, to produce radiation below 1000 A of usable intensity, one must use a high voltage spark discharge. The disadvantage of the spark discharge is that high frequency electrical noise is radiated and this is very hard to shield against.

The hot filament arc discharge in hydrogen produces an over-all, more intense spectrum than the cold cathode discharge. The intensity ratio is only a factor of two or three; however, the ratio of atomic to molecular line intensities is much greater for the hot filament arc discharge. In both types of discharge using a hydrogen-helium mixture, nearly monochromatic radiation at 1216 A is produced.

C. THE DUOPLASMATRON

The Duoplasmatron was developed about twelve years ago as a highly efficient source of protons. After its publication[22] in 1956 a
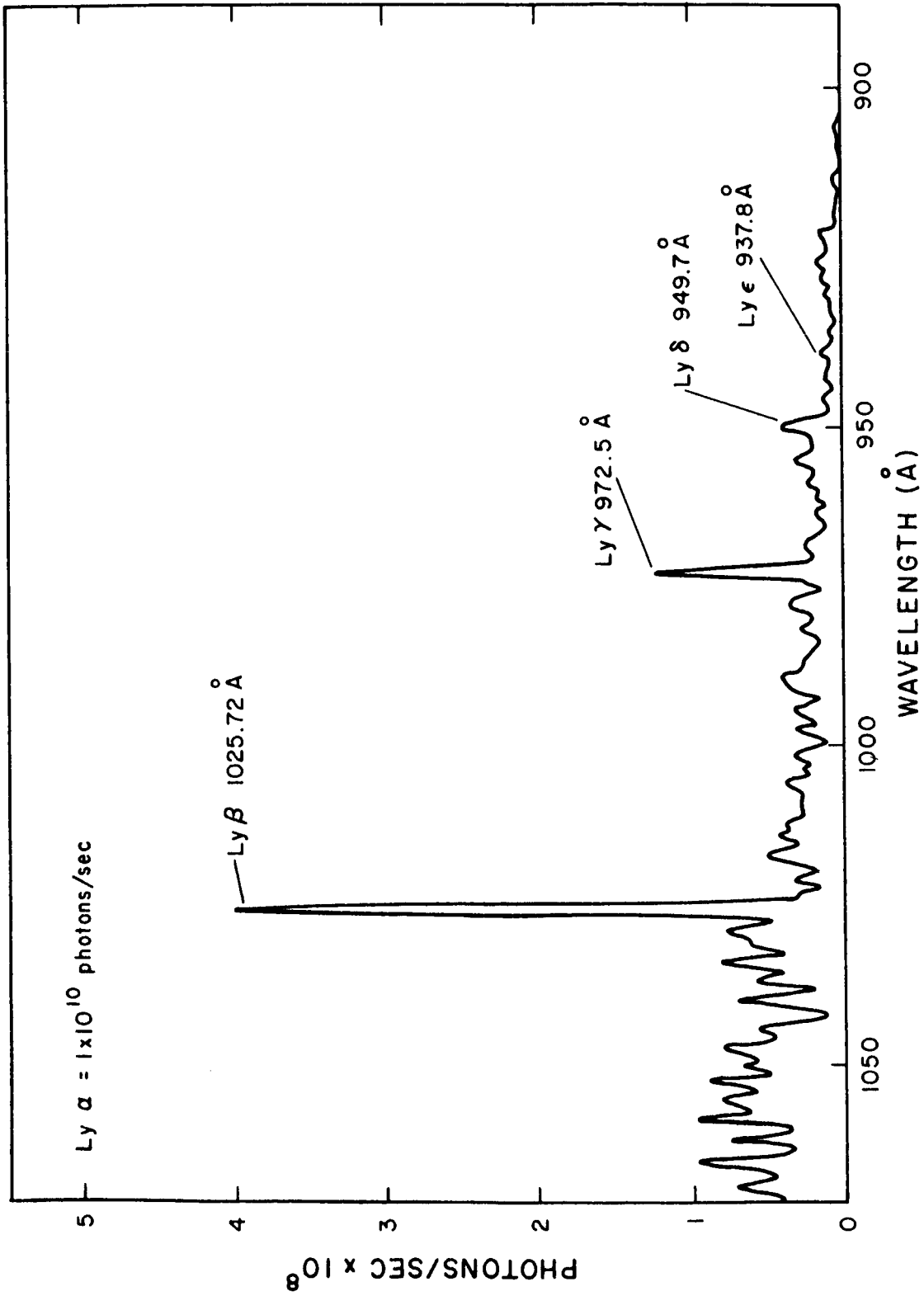
Figure 16. Lyman series of atomic hydrogen obtained in an H_2-He mixture with the hot filament discharge lamp. The intensity of the Lyman-alpha line is given at the top of the figure.

number of variations were designed and used as ion or electron sources
for such applications as accelerator ion sources and ion propulsion
devices.[20,23,24] A further application was suggested by Herzog;[5]
namely, that the highly concentrated plasma of a Duoplasmatron possibly
would emit intense vacuum ultraviolet radiation.

In the spectral region below 1000 A conventional light sources
are of the high voltage pulsed type with their inherent disadvantages that
they radiate electrical noise and are difficult to operate at a constant
light intensity output. Thus, it is desirable to look for a light source
which emits radiation below 1000 A of comparable intensity to the high
voltage pulsed type but which operates from a D.C. supply. The hot fila-
ment type of light source falls into this category with the exception of
light intensity. It was felt, therefore, that with the combination of hot
filament and axial magnetic field as found in the Duoplasmatron that the
light intensity would be comparable with the high voltage pulsed light
sources.

A preliminary measurement of the total intensity between 1050 A
and 1350 A was made using a nitric oxide ion chamber with a Duoplasmatron
which was currently being used as an ion source. The source had an anode
opening of 0.008 inches. Using hydrogen in the Duoplasmatron with an arc
current of 300 mA, an intensity of approximately 10^{12} photons/sec/cm^2 was
measured at a distance of 25 cm from the anode opening for the 1216 A
Lyman-alpha line. This is based on the assumption that 50 percent of
the ion chamber response was due to the 1216 A line--an assumption which

is normally true for a hot filament-type hydrogen lamp. Subsequently a Duoplasmatron light source was designed, built, and tested

The principle of the Duoplasmatron can briefly be described as follows: A low pressure arc discharge in hydrogen, typically 20 to 100 microns pressure, is constricted by a funnel-shaped baffle placed between the electron-emitting cathode (hot filament) and the anode. A strong axial magnetic field of approximately 2000 oersteds is developed between the baffle and the anode by a pole piece arrangement similar to those used as magnetic lenses in electron microscopes, this further constricts the discharge to a narrow plasma beam along the axis. If the anode has a central opening, a very intense ion or electron beam can be extracted from the plasma. Any gas can be used to produce the ions provided the gas does not poison the filament.

1. Design Considerations

In the Duoplasmatron the plasma density on the axis near the anode increases quickly with the magnetic field strength, and after passing a flat maximum slightly decreases. In practice, this means one has to operate the Duoplasmatron above a minimum magnetic field strength to provide a maximum plasma density on the axis. In conventional Du-plasmatrons the magnetic field is generated by a solenoid of 2000 to 7000 amp turns, providing a magnetic field of the order of 2000 oersteds between the pole pieces. However, it would appear that a permanent magnet of equivalent strength would be equally as efficient as a solenoid

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and at the same time have the following advantages: (a) no power supply
for the magnetic field is needed; (b) since the heat generated in the
solenoid is of the same order as the heat generated by the arc, then for
a given cooling rate a higher arc current can be drawn if the solenoid
is replaced by a permanent magnet; (c) since the baffle electrode, which
forms one pole of the magnetic field, operates at a different electrical
potential than the anode, which forms the other magnetic pole, it is
necessary in the case of a solenoid to have an additional air gap in
the path of the magnetic flux through the iron enclosure to provide
electrical insulation. For a given magnetic field strength this requires
additional magnetic induction. This is avoided if one chooses ceramic
permanent magnetic material, which is electrically insulating. (d) There
are ceramic magnets on the market which have an exceptionally high coer-
cive force, typically around 2000 oersteds.[26] That means the required
magnetic length is relatively small; therefore, less iron is needed and
since the ceramic material itself is much lighter than copper, the whole
assembly becomes considerably shorter and lighter than an equivalent
design employing a magnet coil.

2. Construction

A sectional view of the Duoplasmatron is shown in Fig. 17.
The magnetic field is provided by three rings of highly-oriented barium
ferrite permanent magnetic material (Indox V) which are magnetized in the
direction of their axis. This provides a field of 7000 oersteds between
the baffle aperture and the slit holder. The magnetic flux goes from one

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AIR OUT

SOURCE FLANGE
(MILD STEEL)

CERAMIC PERMANENT
MAGNETIC RINGS

COVER FLANGE
(MILD STEEL)

BAFFLE ELECTRODE
(MILD STEEL)

AIR COOLING

FILAMENT FEED THROUGH
2.5 V AT 10A

GAS FEED

AIR COOLING

METAL GASKETS

AIR COOLED COPPER
ANODE

MONOCHROMETER
ENTRANCE SLIT 1/8" × .050"

CERAMIC RING

STAINLESS STEEL
RETAINER RING

−80V

4 kΩ

−42V
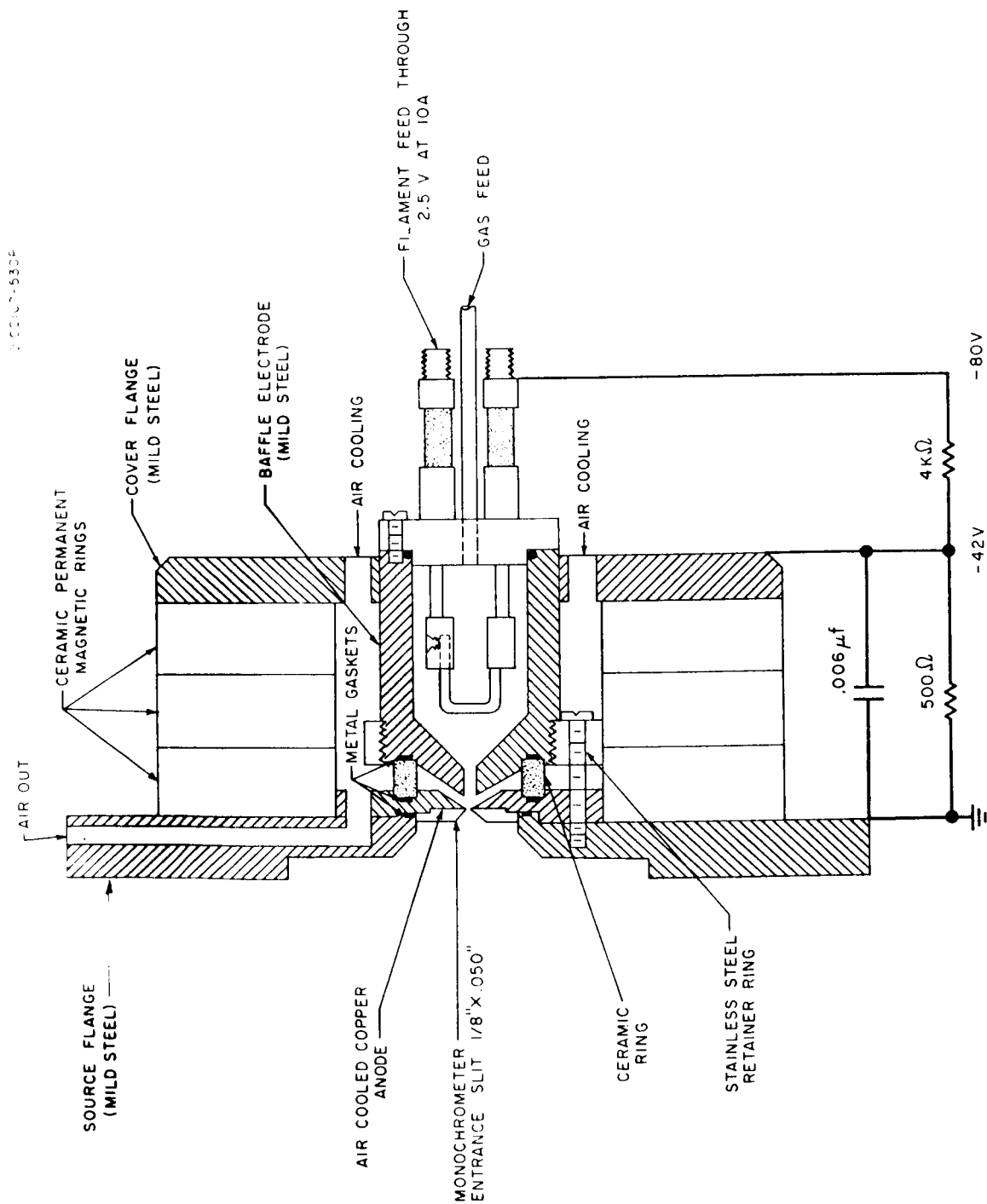
.006 μf

500 Ω

SCALE = 1 in.

Figure 17. Duoplasmatron light source. The voltage distribution shown
is typical under discharge conditions in hydrogen.

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pole of the magnet through the source flange and the slit holder over the gap, through the wall of the baffle electrode, and then through the cover plate to the other pole of the magnet. The slit--the two halves of which are screwed to the slit holder--is held by the strong magnetic field between the apex of the baffle electrode and the slit holder which slides in the source flange. This way the slit can easily be pulled out and inspected. The magnetic field presses the slit against the anode which is an air-cooled disc of copper. The cooling disc, a ceramic spacer ring and the baffle electrode--onto which is screwed a stainless steel retainer ring--are sealed to the source flange with six screws simultaneously, having indium or gold O-rings between each other. The baffle electrode is closed by a feed-through cap, which carries the gas inlet tube and two ceramic terminal bushings which hold two studs between which the filament is mounted. The filament is platinum mesh wire, which is dipped in a suspension of barium carbonate and activated in a hydrogen atmosphere. A cooling fan, mounted on the cover plate, blows air through twelve holes in the cover plate, along the baffle electrode, through twelve holes in the cooling disc, and finally out through twelve channels in the source flange.

The circuit diagram for the arc power supply is shown in Figure 18. The supply is current stabilized by simply inserting an amperit ballast tube in series with the load. Figure 19 shows the current-voltage characteristics of a typical tube. The power supply was constructed with
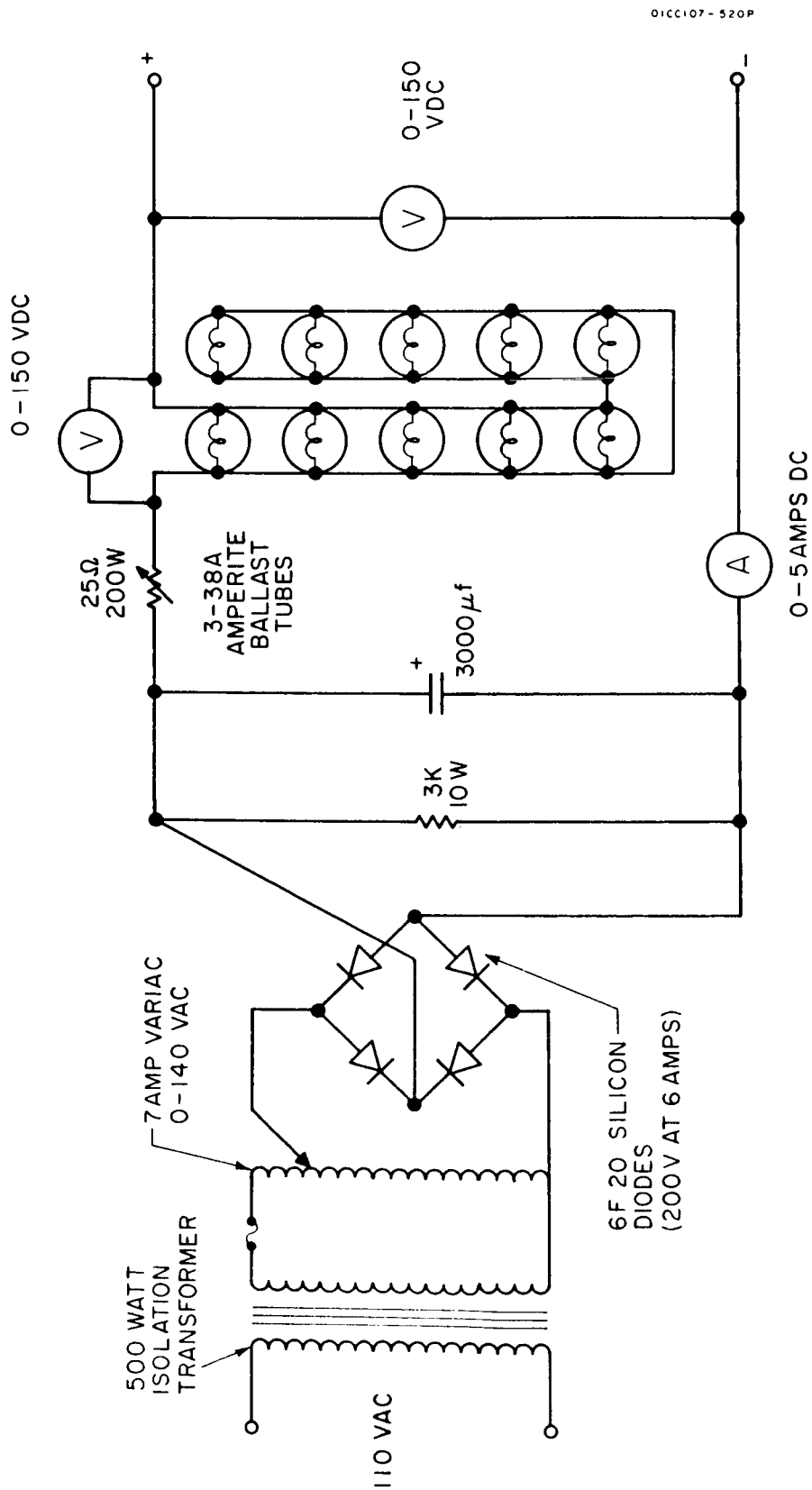
OICC107-520P

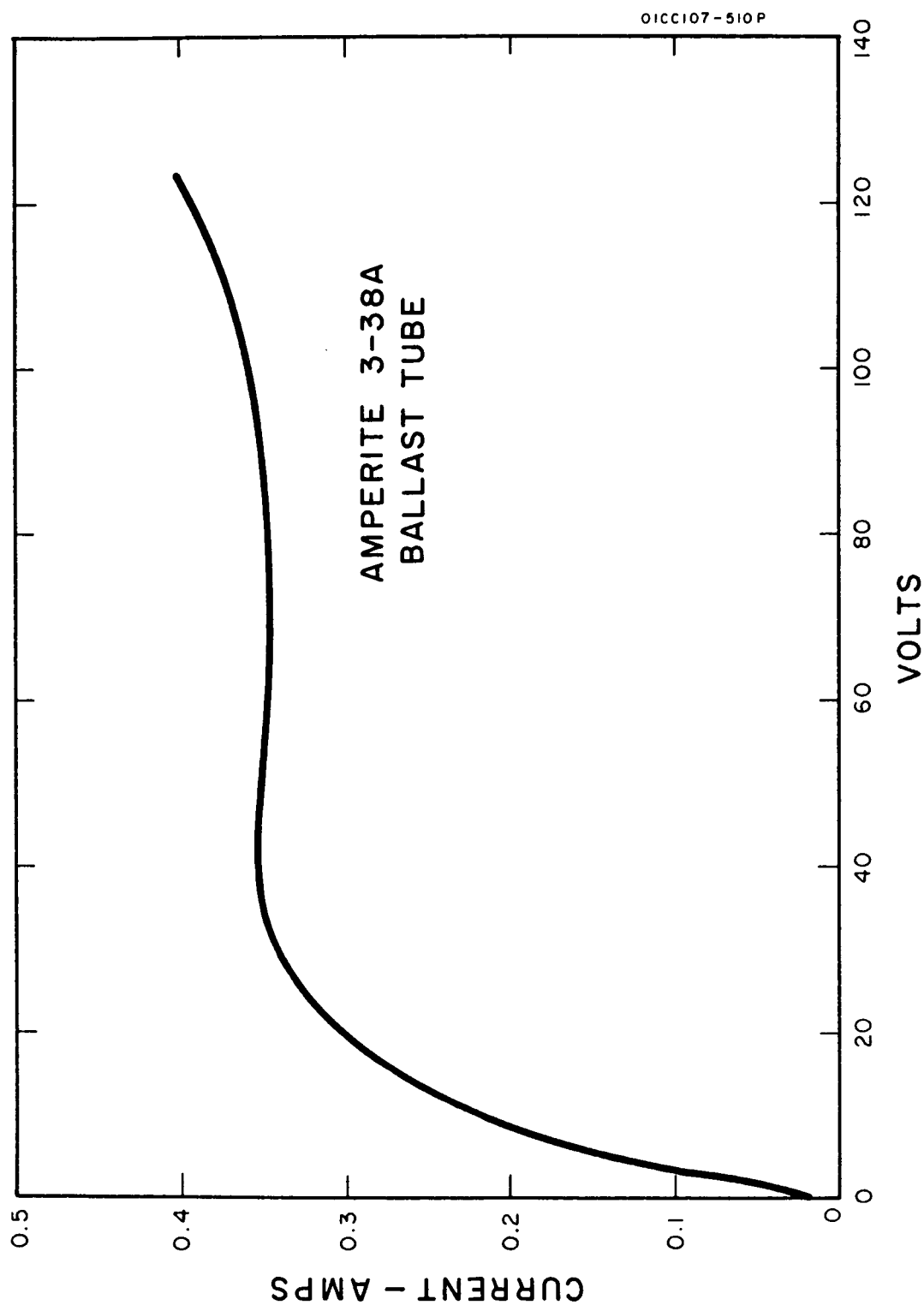Figure 18. Current regulated power supply from 0.3 to 3 amps.

OICCI07-5IOP

Figure 19. Current-voltage characteristic of an amperite 3-38A ballast tube.

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ten amperite 3-38 A ballast tubes in parellel in order to provide current stabilization for 0.3 amps to 3 amps by switching in the number of tubes required to provide the desired arc current.

3. Results

The Duoplasmatron, as shown in Figure 17, has been operated successfully both as an ion source and as a vacuum ultraviolet light source. The extractor aperture of the Duoplasmatron ion source was replaced by a slit assembly 1/8 inch high by 50 microns wide. The slit assembly constituted the entrance slit of a $\frac{1}{2}$ M Seya-type vacuum monochromator having a reciprocal dispersion of 16 A/mm. Under such conditions a wavelength resolution of approximately 2 A was obtained. No windows were used between the light source and the monochromator since no suitable materials exist which will transmit radiation below 1050 A (the short wavelength transmission limit of lithium fluoride). However, due to the low operating pressure of the Duoplasmatron and the small slit area, a pressure of 1×10^{-4} torr was maintained in the monochromator chamber without the use of a differential pumping chamber between the light source and monochromator. When the discharge was started, the pressure in the monochromator decreased by a factor of two or three. This, apparently, is due to the intense ionization in the vicinity of the entrance slit impeding the flow of neutral gas through the slit into the monochromator. The entrance slit is at a positive potential relative to the baffle in the Duoplasmatron

The ultraviolet detector was an EMI 9514B photomultiplier tube sensitized to vacuum ultraviolet radiation by coating its envelope with sodium salicylate. The quantum efficiency of this scintillator has been measured from 2000 A down to 800 A and found to be constant.[9] Although it is probable that the constancy of the quantum yield of sodium salicylate continues in the region of our measurements down to 550 A, one must be careful in comparing the relative intensity of two lines rather widely separated as the efficiency of diffraction gratings in the vacuum ultraviolet region of the spectrum is not constant with wavelength.[17]

Figure 20 shows the spectrum of hydrogen between 1800 A and 900 A. It is a typical hydrogen spectrum with the molecular continuum to longer wavelengths of 1650 A and the many-lined molecular spectrum to shorter wavelengths with the atomic lines of the Lyman series, alpha and beta, at 1215.7 A and 1025.7 A, respectively. However, it does differ from the spectrum produced in a hydrogen glow discharge (cold cathode type) in that the atomic resonance line at 1215.7 A is several times more intense than the most intense molecular line, usually 1608 A. As the arc current was varied from 0 to 0.9 amps, the light intensity increased almost linearly--the molecular lines increasing at a somewhat slower rate than the atomic lines. This result can be correlated with the analysis of the beam composition as a function of arc current as reported by Moak et al.[20] who found a rather linear and more rapid increase in the atomic ion content than in the molecular ion content.
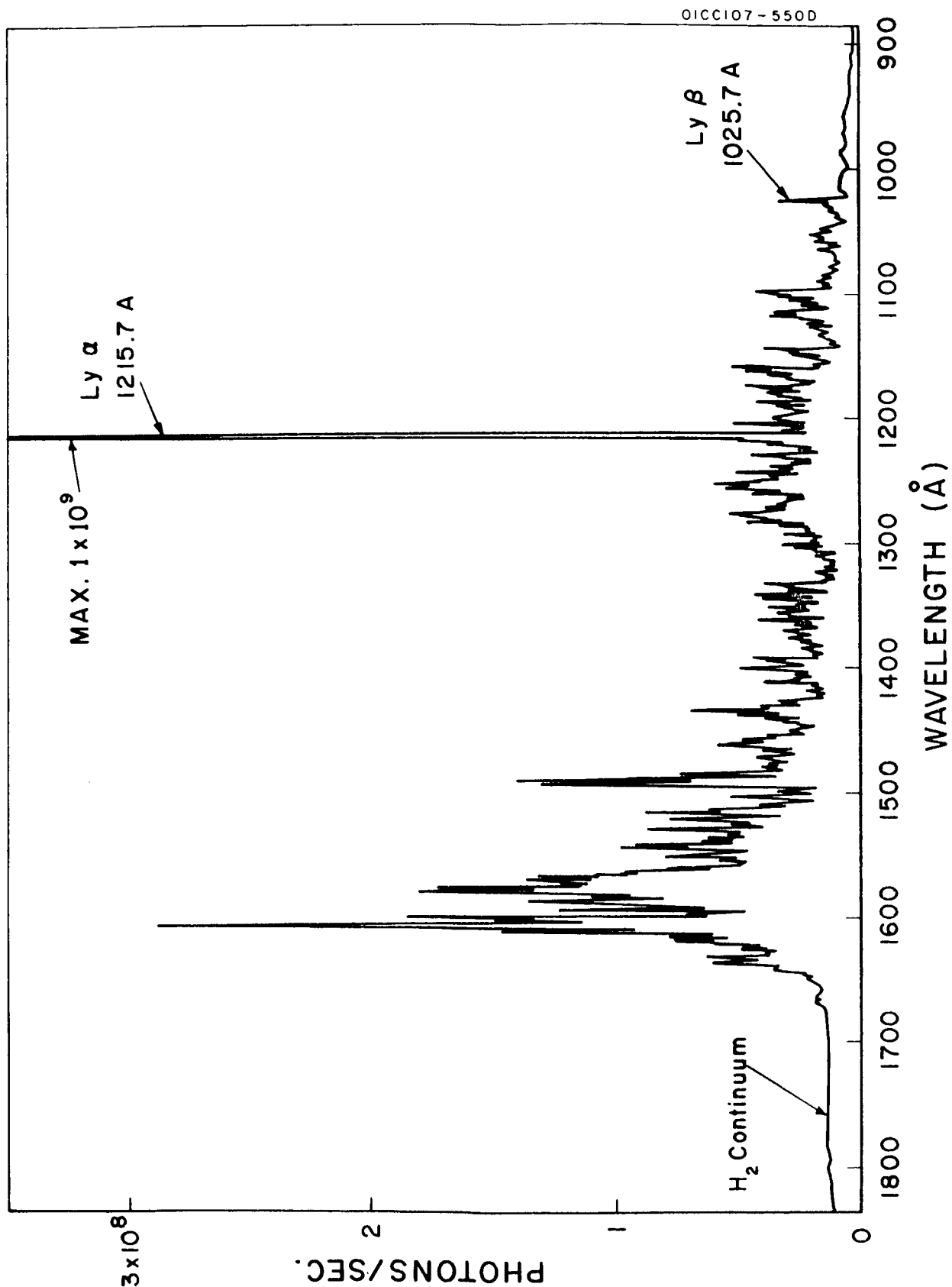
OICCIO7-550D

Figure 20. Hydrogen spectrum taken with an arc current of 0.9 amp. Wavelength resolution is approximately 2 Angstroms.

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An argon spectrum from 550 A to 1100 A is shown in Fig. 21.
The arc current was 1.5 amps with 30 volts between anode and filament.
As the arc current increased from zero, the radiation from excited
neutral atoms increased to a maximum around 1 amp and then remained
constant or even decreased slightly as the arc current increased further;
however, the radiation from the singly and doubly ionized atoms continued
to increase. At 3 amps the 879.6 A and 878.7 A lines of A III were a
factor of five more intense than shown in Figure 21, whereas the A II
series increased by only a factor of two. The presence of an air leak
was indicated by radiation from atomic nitrogen and oxygen.

That the magnetic field confines the discharge to a very
intense radiating plasma along the axis is evidenced by the fact that if
the ceramic magnets are removed one by one, the light intensity decreases
rapidly to the point of essentially zero light intensity at zero magnetic
field.

The Duoplasmatron is suitable as a D.C. light source pro-
ducing considerable intensity in the spectral region below 1000 A; however,
the results presented here, in argon, are somewhat less intense than those
of a 6 kv, 60 pps spark discharge. By increasing the arc discharge current,
it appears possible to increase the intensity of the radiation to the point
where it is comparable to that of the high voltage pulsed discharge.
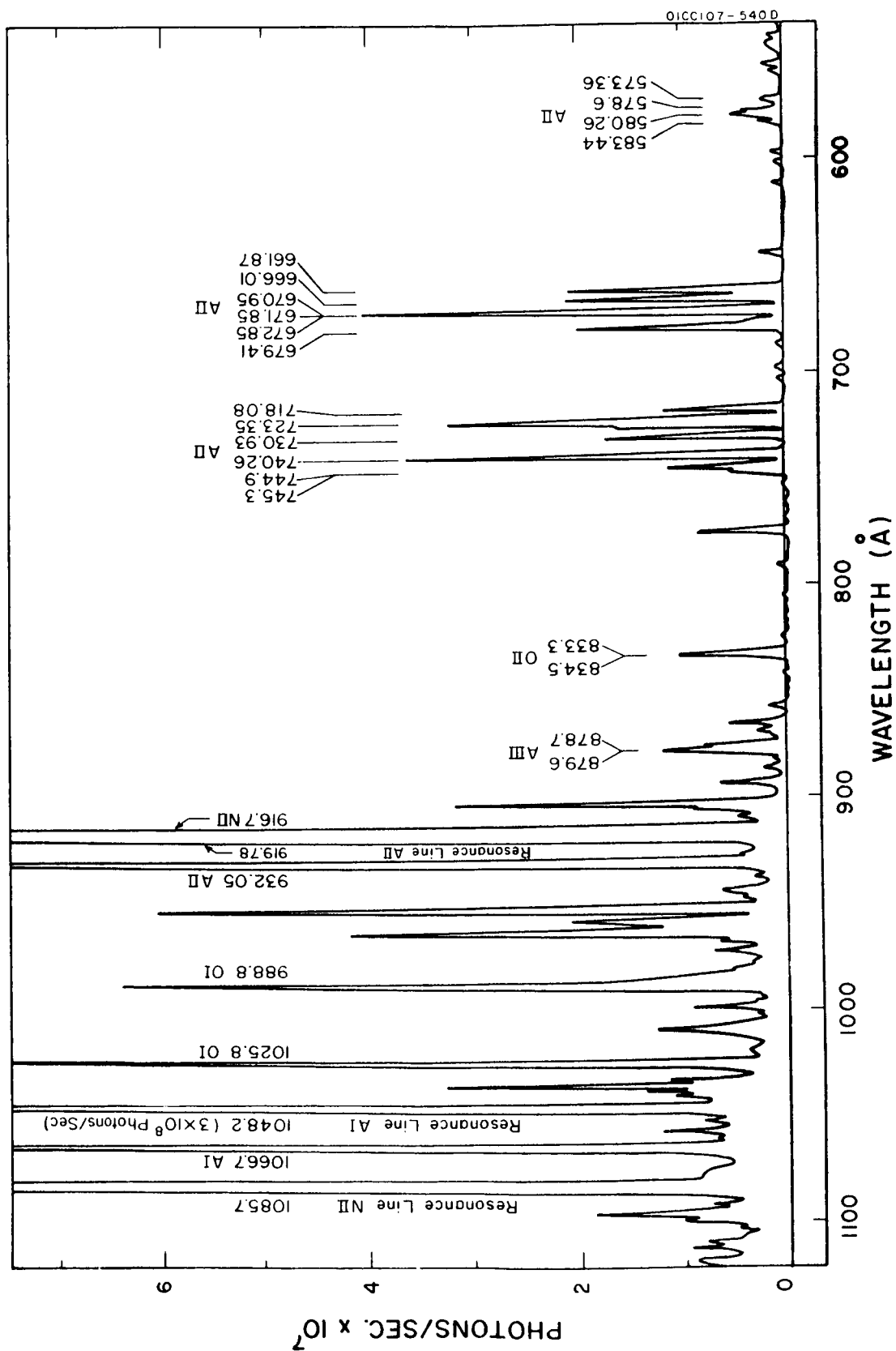
Figure 21. Argon spectrum taken with an arc current of 1.5 amp.

D. MICROWAVE DISCHARGE

The first reported use of microwave frequencies to excite a discharge for use as a spectroscopic light source was by W. F. Meggers at the National Bureau of Standards.[27] He used a 110 Mc electrodeless discharge to excite the spectrum of Hg^{198} using the green 5461 A line as a standard of length. Jacobsen and Harrison,[28] studying these standard lamps, reported that the life and intensity of the lamps increased with frequency in the range 10 to 3000 Mc. Since then, several other investigators[29-34] have described electrodeless discharge tubes excited in a microwave cavity. They used a Raytheon Microtherm Generator to produce radiation of 2450 Mc at a power output of 125 watts. Of these, the first report of their use as vacuum ultraviolet light sources was by Wilkinson.[33,34] Frost and McDowell[31] used them to produce line spectra in air and argon down to 600 A. P. Warneck[32] has described the use of a microwave discharge in hydrogen to produce the 1215.7 A Lyman-alpha line of atomic hydrogen for photochemical research. Recently, the Jarrell-Ash Company has produced the rare gas continua in a microwave cavity (see Section II). These light sources apparently are based on the researches of Wilkinson.[33]

The advantages of an electrodeless discharge are the absence of sputtered electrode material and impurities imbedded within the electrodes. The absence of sputtering prolongs the life of the windows.

The microwave light source investigated here was simply a long quartz tube placed within a microwave cavity. Figure 22 shows the quartz
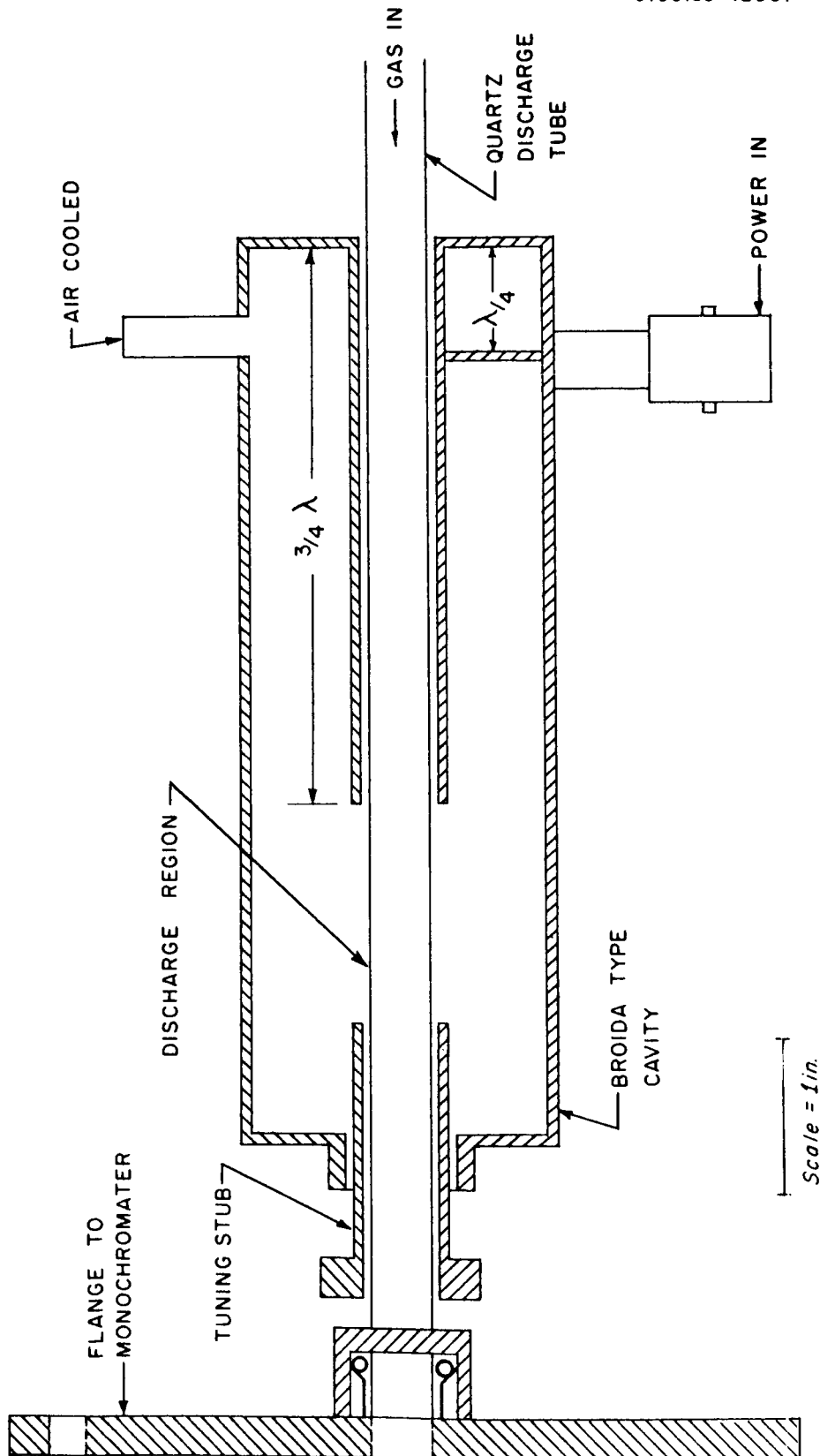
Figure 22. Microwave light source consisting of a quartz discharge tube and a microwave cavity.

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tube inside the cavity which has to be air-cooled to dissipate the intense heat generated by the discharge. The quartz tube is sealed by a Teflon ferrule through a swagelok fitting to a water-cooled flange. A 2450 Mc, 125 watt microwave generator was used to excite the cavity. By adjusting the tuning stub, maximum coupling could be achieved and, therefore, maximum light intensity. The hydrogen spectrum produced in the microwave cavity was similar to that of the D.C. glow and hot filament arc discharges although somewhat weaker. Like the hot filament arc, the microwave discharge in hydrogen tends to favor the atomic spectra. In a hydrogen-helium mixture, the microwave discharge produces perhaps the most monochromatic source of Lyman-alpha radiation. Figure 23 shows a spectrum taken with the hydrogen-helium mixture.

Spectra were observed in air and argon below 1000 A, but these were very weak. It is felt that the use of a capillary of a few mm bore rather than the 10 mm bore used here, would provide more intensity in the region below 1000 A.
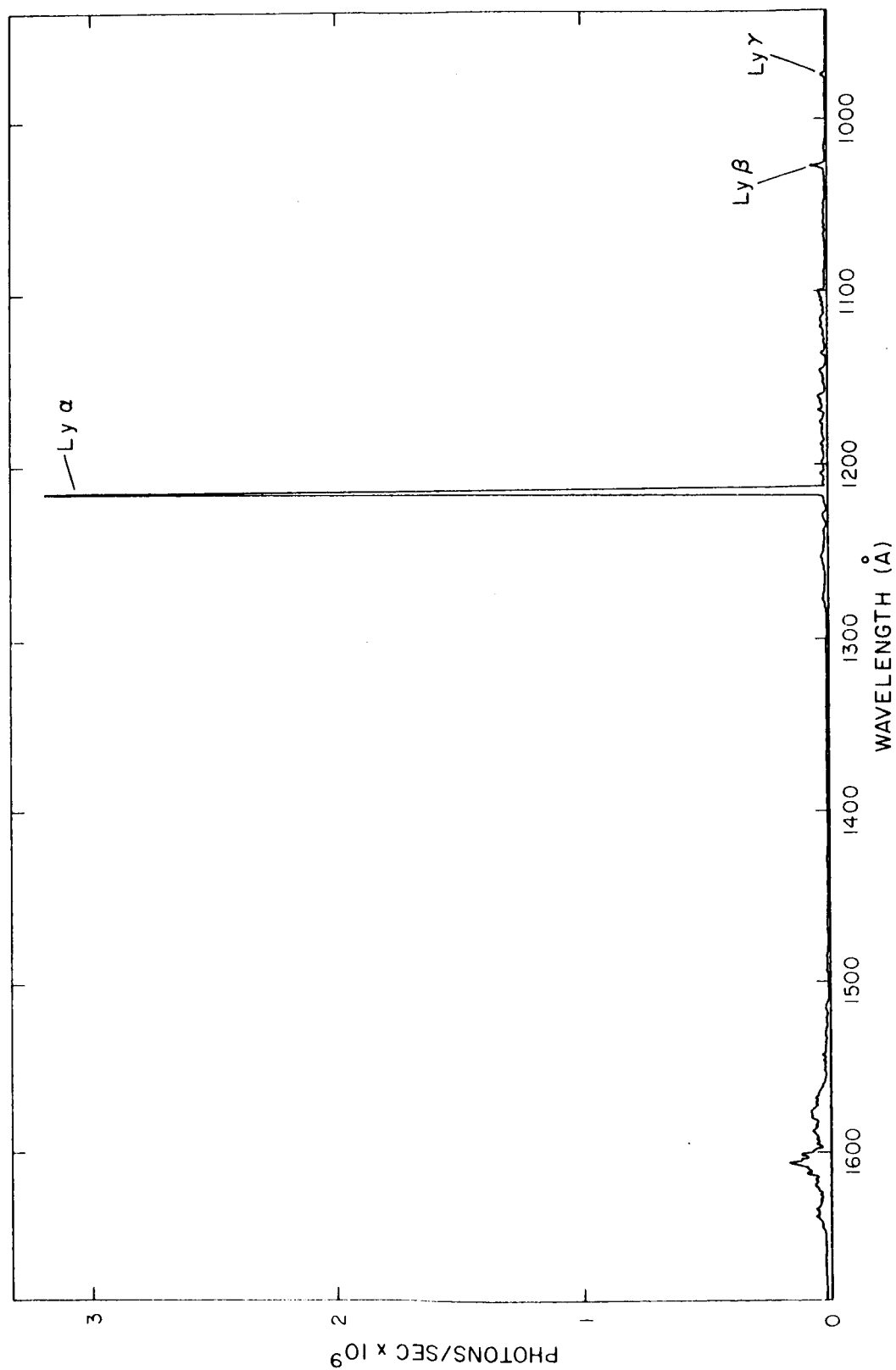
Figure 23. Hydrogen spectrum excited by microwaves in an H_2-He mixture. The spectrum is essentially monochromatic at Lyman-alpha.

IV. CONCLUSIONS

From the foregoing discussion it appears that several light sources exist which produce useful continua from 3500 A to 600 A of sufficient intensity to measure (employing photoelectric detection techniques) (a) absorption cross sections of gases and crystals, and (b) reflectance and transmittance of thin films. In addition, it appears that in most cases, a resolution of one Angstrom or better can be achieved.

For photoionization measurements, it is possible to use the continua, especially the Hopfield continuum, if wider entrance and exit slits are used. The intensities are marginal, but by sacrificing resolution for intensity, one can still get valuable data previously unobtainable since the conventional high voltage spark spectrum below 1000 A has gaps between lines of as much as 20 A. However, the high voltage spark light source is still one of the most useful sources due to its greater intensity and low operating pressures eliminating elaborate differential pumping.

Geophysics Corporation of America
  Bedford, Massachusetts
    August 1962

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